SPECIES STATUS ASSESSMENT
EMPEROR PENGUIN
(*APTENODYTES FOSTERI*)

Emperor penguin chicks being socialized by male parents at Auster Rookery, 2008. Photo Credit: Gary Miller, Australian Antarctic Program.

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EXECUTIVE SUMMARY

Penguins are flightless birds that are highly adapted for the marine environment. The emperor penguin (*Aptenodytes forsteri*) is the tallest and heaviest of all living penguin species. Emperors are near the top of the Southern Ocean's food chain and primarily consume Antarctic silverfish, Antarctic krill, and squid. They are excellent swimmers and can dive to great depths. The average life span of emperor penguin in the wild is 15 to 20 years.

Emperor penguins currently breed at 61 colonies located around Antarctica, with the largest colonies in the Ross Sea and Weddell Sea. The total population size is estimated at approximately 270,000–280,000 breeding pairs or 625,000–650,000 total birds. Emperor penguin depends upon stable fast ice throughout their 8–9 month breeding season to complete the rearing of its single chick. They are the only warm-blooded Antarctic species that breeds during the austral winter and therefore uniquely adapted to its environment. Breeding colonies mainly occur on fast ice, close to the coast or closely offshore, and amongst closely packed grounded icebergs that prevent ice breaking out during the breeding season and provide shelter from the wind.

Sea ice extent in the Southern Ocean has undergone considerable inter-annual variability over the last 40 years, although with much greater inter-annual variability in the five sectors than for the Southern Ocean as a whole. The overall increase in Antarctic sea ice extent since the 1970s reversed in 2014, with subsequent rates of decrease in 2014–2018. The rapid decreases reduced the Antarctic sea ice extents to their lowest values in the 40-y record. However, the Southern Ocean and four of the five sectors—all except the Ross Sea—have experienced at least one period since 1999 when the yearly average sea ice extent decreased for three or more straight years only to rebound again afterward and eventually reach levels exceeding the sea ice extent preceding the 3 years of decreases. Therefore, the decrease in sea ice that started in 2014 is no assurance of a long-term negative trend.

Climate change is the only major stressor that affects the emperor penguin now and into the future because increased warming air and sea temperatures will affect the extent and duration of sea (fast) ice and ~~relatedly~~ subsequently prey abundance and distribution around the continent of Antarctica. The projections of sea ice condition and the emperor penguin population are directly related, and sea ice serves as a proxy measure of all important habitat factors for the species. Therefore, the resiliency of an emperor penguin colony is tied to the sea ice conditions at a particular colony. Additionally, climate change-induced ocean acidification is projected to affect the Southern Ocean ecosystem and prey species of emperor penguin. Other minor anthropogenic stressors on the emperor penguin population include tourism, contamination of the marine environment, and krill fisheries, but these minor effects are not driving factors of the emperor penguin's viability.

We discuss three plausible future scenarios based on existing work that projected sea ice conditions and the response of emperor penguins under a low, moderate, and high emissions scenario uo. Using Global Circulation Models from CMIP3 and CMIP5~~ ensemble models~~, as well as the Community Earth System Model Large Ensemble~~ project that contributed to CMIP5~~. ~~Simulations were run~~ The low emissions scenario~~s of the~~achieves the Paris A~~a~~greement goals of

Commented [HZ1]: I think some part of this would actually sit better at the end of the second paragraph, and it would help make the transition to the discussion of physical changes in the sea ice smoother while also making it clear the link between penguin survival and sea ice in particular.

limiting warming to either~~s that reach~~ 1.5 or ~~and~~ 2 °C by the end of the century, the ~~; under~~ moderate emissions scenario is SRES A1B from CMIP3 (which is consistent with RCP 6.0 in CMIP5) and the ~~; and under~~ high emissions scenario is RCP 8.5 from CMIP5. Based strictly on the projected increase in global temperature, the Paris goals would fall at the high end of RCP 2.6 projections and within the projected range of RCP 4.5.

Penguins could respond to climate change in two main ways: ~~,~~ dispersal and adaptation. The species has so far shown little evidence of adaptive capacity and the paleontological record shows that the most likely response to climate change is dispersal to new habitat. Emperor penguins have continued to inhabit their resident colonies that have experienced loss of fast ice for one or more breeding seasons (i.e., Cape Crozier; Pointe Géologie), relocated to nearby colonies after the early break out of sea ice for consecutive years (i.e., Halley Bay to Dawson-Lambert), and likely relocated after the first documented loss of a breeding colony because of unsuitable sea ice conditions (i.e., Dion Islets).

The SSA framework considers what the emperor penguin requires for viability by characterizing the species' status in terms of resiliency, redundancy, and representation (3Rs). Under low and moderate emissions scenarios, the 3Rs show similar patterns. The most at risk colonies are in the eastern Weddell Sea and Indian Ocean in Dronning Maud, Enderby, and Kemp Lands. ~~The effects to o~~Other colonies in the southern Indian Ocean and Western Pacific Ocean in East Antarctica, and in the Bellingshausen-Amundsen Seas in West Antarctica ~~have~~ exhibit more varied projections that depend~~ing~~ on the scenario. Colonies may decline by less than 30% ~~all the way to declining~~ or by more than 90%. Breeding colonies that experience steeper declines and greater annual variability in sea ice are more likely to be negatively affected. Under the high emissions scenario, all 3Rs significantly decrease because of very poor future sea ice conditions. Colonies in the Ross Sea and western Weddell Sea are projected to be the most resilient under every scenario because these colonies will have ~~higher quality~~ moore favorable sea ice conditions at the end of the century relative to the other colonies. The Ross Sea is likely going to be the last stronghold for the species, but even these colonies ~~would be~~are expected to declin~~e~~e~~ing~~ at the end of the century under ~~a~~ moderate and high emissions scenarios.

Total Emperor Penguins (2020)	**Approximately 270,000–280,000 breeding pairs; 625,000–650,000 total birds**		
	Aptenodytes species rear on average 0.6–0.8 chicks per pair; breeding success varied over six decades between 3–86% for emperor penguin at the Point Géologie colony.		
Scenario Projections by 2100	**Global Temperature Increase (°C)**	**Median Population Decline (%)**	**Median Population Growth Rate (%)**
Low Emissions	1.5–2	31–44	-0.07–0.34
Moderate Emissions	3	78	-3.2
High Emissions	5	86	-4.0

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CHAPTER 1: INTRODUCTION

We received a petition on December 5, 2011, from the Center for Biological Diversity to list the emperor penguin (*Aptenodytes fosteri*) as threatened or endangered under the Endangered Species Act (Act). On January 22, 2014, we published in the Federal Register (79 FR 3559) a 90-day finding that found the petition presented substantial scientific and commercial information that the petition action may be warranted.

This report summarizes the results of a species status assessment (SSA) of the emperor penguin. The SSA framework intends to be an in-depth review of a species' biology and threats, an evaluation of its biological status, and an assessment of the resources and conditions needed to maintain long-term viability. An SSA does not result in a decision by the Service on whether the emperor penguin should be proposed for listing as a threatened or endangered species under the Act, but instead provides a review of the available information strictly related to the biological status of the species. The Service will make a decision after reviewing this document and all relevant laws, regulations, and policies. We will publish any proposed listing decision in the *Federal Register* with opportunities for public input.

Using the SSA framework (Figure 1), we considered what the species requires for viability by characterizing the status of the species in terms of 3Rs: Resiliency, Redundancy, and Representation (Service 2016, entire; Smith *et al*. 2018, entire). For this SSA report, we generally define viability as the ability of species to sustain populations in the wild over time.

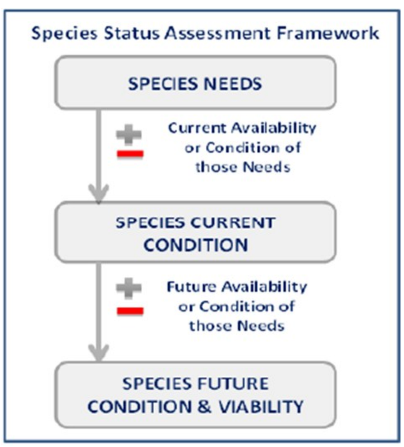


Figure 1. Species Status Assessment Framework

Resiliency describes the ability of populations to withstand stochastic events (i.e., those that arise from random factors). For example, we can measure resiliency based on metrics of population health, birth rate versus death rate, or population size. Highly resilient populations are better able to withstand environmental variability and/or the effects of anthropogenic activities.

Redundancy describes the ability of a species to withstand catastrophic events. Measured by the number of populations, their resiliency, and their distribution and connectivity, redundancy gauges the probability that the species has a margin of safety to withstand or bounce back from catastrophic events that may involve many populations.

Representation describes the ability of a species to adapt to changing environmental conditions. We measure representation by the breadth of genetic or environmental diversity within and among populations. Representation gauges the probability that a species is able to adapt to environmental changes. The more representation (i.e., diversity) a species has, the more likely it is to adapt to natural or human-caused changes in its environment. In the absence of species-specific genetic and ecological diversity information, we may evaluate representation based on the extent and variability of habitat characteristics across the geographical range.

This SSA report provides a thorough assessment of biology and natural history of the emperor penguin, and assesses demographic risks, stressors, and limiting factors in the context of determining viability and risk of extinction for the species. To evaluate the biological status of emperor penguin into the future, we assessed a range of scenarios to allow us to consider the species' resiliency, redundancy, and representation (the 3Rs).

The SSA report includes the Introduction (Chapter 1); Ecology of the Emperor Penguin (Chapter 2); Current Conditions (Chapter 3); Projected Future Conditions, including a description of viability in terms of resiliency, redundancy, and representation (Chapter 4); Catastrophic Events (Chapter 5); Uncertainties (Chapter 6); and a Summary (Chapter 7). This report represents a compilation of the best available scientific and commercial information and a description of the present and likely future risk factors to emperor penguin.

CHAPTER 2: ECOLOGY OF THE EMPEROR PENGUIN

Taxonomy

The emperor penguin (*Aptenodytes forsteri*) is a recognized entity and was probably first sighted on Captain James Cook's second voyage (1772–1775) to discover Terra Australis Incognita or the Unknown Land of the South (Wienecke et al. 2013, p. 24; ITIS 2020, unpaginated). The emperor penguin is named in honor of Captain Cook's naturalist, Johann Reinhold Forster, who was the naturalist on board the Resolution, Captain Cook's second voyage (Wienecke et al. 2013, p. 24). In 1844, the head of the ornithology section of the British Museum in London (George Robert Gray) separated emperor penguins from kings penguins (*Aptenodytes patagonicus*), their closest relatives (Wienecke et al. 2013, p. 24; ITIS 2020, unpaginated).

Genetics

The emperor penguin was reported to be panmictic—genetically homogeneous at the continent scale—which implies the entire species share a common demographic history (Cristofari et al. 2016, p. 2). However, the most recent studies on the genetic differentiation of emperor penguin colonies revealed at least four metapopulations, with some degree of connectivity among the metapopulations, and very high connectivity between breeding colonies within each metapopulation (see Figure 2.1, Younger et al. 2017, p. 3888). The fact that emperor penguins travel widely as juveniles, move among breeding colonies, and share molting locations indicates that dispersal is providing gene flow among populations (Younger et al. 2017, p. 3894). Not all colonies have been included in genetic analysis (Younger et al. 2017, p. 3897). Therefore, more metapopulations may exist but are not yet known.

The colonies within the Ross Sea are genetically distinct from colonies in East Antarctica and the Weddell Sea and are the most genetically differentiated population overall (Younger et al. 2015, p. 2219; Younger et al. 2017, p. 3893). However, the Ross Sea is not isolated from other colonies by distance or any oceanographic barriers (Younger et al. 2015, p. 2220). The distinctness dates back to the last ice age when penguins were unable to breed in more than a few locations around Antarctica because of the winter sea-ice extent, and the colonies that existed were located near polynyas, which provided a refuge for emperor penguins (Younger et al. 2015, p. 2223). Polynyas are a stretch of biologically productive open water surrounded by ice, especially in Polar Seas, and are prime foraging habitat for emperor penguins because they provide the closest open water to the colony and have high abundance of food resources (Labrousse et al. 2019, p. 2; NSIDC 2020, unpaginated).

Colonies at distances less than 600 kilometers (km) apart appear to be genetically connected and colonies separated by distances greater than 600 km show less predictable genetic differentiation. For example, emperor penguins at Amanda Bay are not genetically differentiated from those 3,200 km away at Pointe Géologie, whereas they are significantly different from the Fold Island colony that is 790 km away (Figure 2.1). Therefore, connectivity of emperor penguin colonies should not be based exclusively on geographic proximity (Younger et al. 2017, p. 3892).

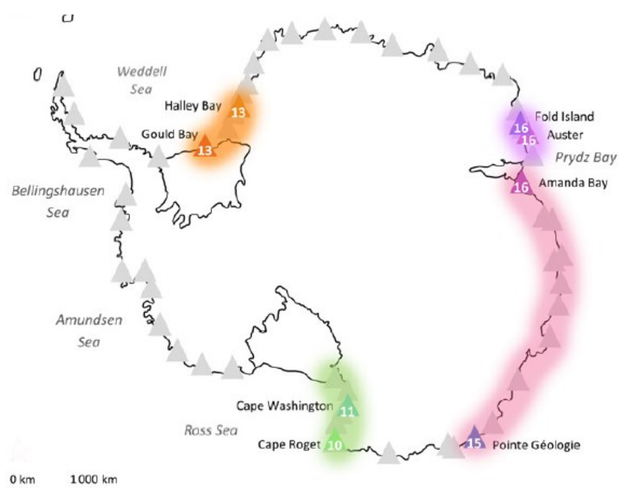


Figure 2.1. At least four metapopulations of emperor penguins: Ross Sea (green), Weddell Sea (orange), Mawson Coast (purple), and Amanda Bay/Point Géologie (pink) (Younger et al. 2017, p. 3892). Gray areas were not analyzed.

Species Description and Ecology

The emperor penguin is the tallest and heaviest of all living penguin species (Australian Antarctic Division 2020, unpaginated). Adults may weigh up to 40 kilograms (88 pounds) and are as tall as 114 centimeters (45 inches) (National Geographic 2020, unpaginated). In proportion to their overall size, they have small bills and flippers to conserve heat (Australian Antarctic Division 2020, unpaginated). Penguins are flightless birds that are highly adapted for the marine environment. They are excellent swimmers and can dive to great depths (Australian Antarctic Division 2020, unpaginated). The average life span in the wild is 15 to 20 years (National Geographic 2020). One generation is estimated at 16 years (Jenouvrier *et al*. 2014, p. 717).

Males and females are similar in plumage and size, although males are slightly larger than females (Wienecke et al. 2013; Global Penguin Society 2020, unpaginated). The head is black and sharply delineated from the white belly, pale-yellow breast and bright yellow auricular patches. Adults have dark grey backs and white fronts with two black bands on the neck. The upper bill is black and the mandibular plates on the lower bill gradually turn pink to orange. Chicks are pale grey, with black head and white patches around the eyes and under the black bill that extend to the chin, like a white mask. Chicks go through two layers of down (hatching and cloverdown) before growing their juvenile plumage (Global Penguin Society 2020, unpaginated).

Figure 2.2. Emperor penguin adults and chicks (Global Penguin Society 2020, unpaginated).

Emperor penguins have large reserves of energy-giving body fat and a relatively low level of activity during winter. They have excellent insulation in the form of several layers of scale-like feathers. Their feet are adapted to the icy conditions and have strong claws for gripping the ice. Like other animals that live in Polar Regions, special fats in their feet prevent them from freezing. Emperor penguins also have the ability to recycle their own body heat; the arteries and veins lie close together so that blood is pre-cooled on the way to a penguin's feet, wings, and bill and warmed on the way back to the heart (Australian Antarctic Division 2020, unpaginated).

The Emperor penguin colony at Pointe Géologie of Terre Adélie in East Antarctica is monitored on an annual basis and has been for more than six decades (Trathan et al. 2020). Only a few other long-term time series of colony size exist at other sites, which include colonies in East Antarctica and the Ross Sea (Trathan et al. 2020, p. 2; Williams 1995, p. 157). However, most of the existing colonies have never been, and probably never will be visited by humans, and will never become the focus of long-term demographic studies. They are too remote from occupied research stations and the emperor penguin breeding season occurs during the winter when ground visits to breeding colonies are impossible with existing techniques (Jenouvrier et al. 2014, p. 715; Ancel et al. 2014, p. 1). Behavior patterns on land during the breeding season are well known but much of the species ecology at sea is poorly described.

Reproduction and Breeding Cycle

The emperor penguin has a long breeding cycle, approximately 8–9 months, initiating breeding in the austral fall to complete the rearing of its single chick within a year (Williams 1995, pp. 157–159). Austral relates to the southern hemisphere and boreal relates to the northern hemisphere (Merriam-Webster 2020, unpaginated); seasons of the year are opposite in the northern and southern hemispheres. For the Austral calendar and emperor penguin life cycle, the seasons are:

Season	Months	Life Cycle Component
Summer	December, January and February	Nonbreeding
Fall	March, April and May	Laying
Winter	June, July and August	Incubating
Spring	September, October and November	Rearing

The emperor penguin is the only warm-blooded Antarctic species that breeds during the austral winter and therefore is uniquely adapted (Trathan et al. 2020, p. 3). The breeding cycle of emperor penguins occurs when primary ocean production is lower in the austral winter; thus, penguins have to accumulate energy reserves during the summer that precedes breeding in order to undergo long fasting periods while breeding. *Aptenodytes* penguins (king and emperor penguins) do not build or use nests; instead, they incubate chicks on adult’s feet (Stonehouse 1953, pp. 2–8; Williams 1995, p. 19).

The breeding cycle for the species is synchronous, although the timing may vary slightly between colonies around the continent of Antarctica, with some starting the process sooner or later (Williams 1995, p. 20; Wienecke et al. 2013, in Trathan et al. 2020, p. 3). Regardless of when the process starts, all colonies studied so far have a similar schedule (i.e., breeding cycle) (Trathan et al. 2020, p. 3). For penguin species in general, day length provides the initial predictive information that serves to bring the bird to the breeding area at the optimum time of year, and in the correct physiological state, for breeding to take place (Williams 1995, p. 21). However, the emperor penguin is the exception to this general pattern and is one of the few species of birds where onset of breeding is coincident with decreasing day length, during the austral autumn (Williams 1995, p. 21).

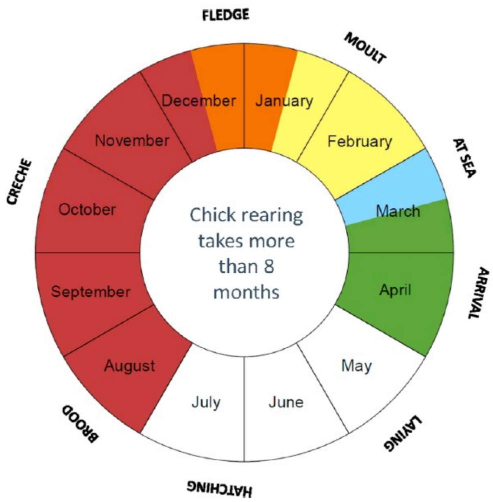
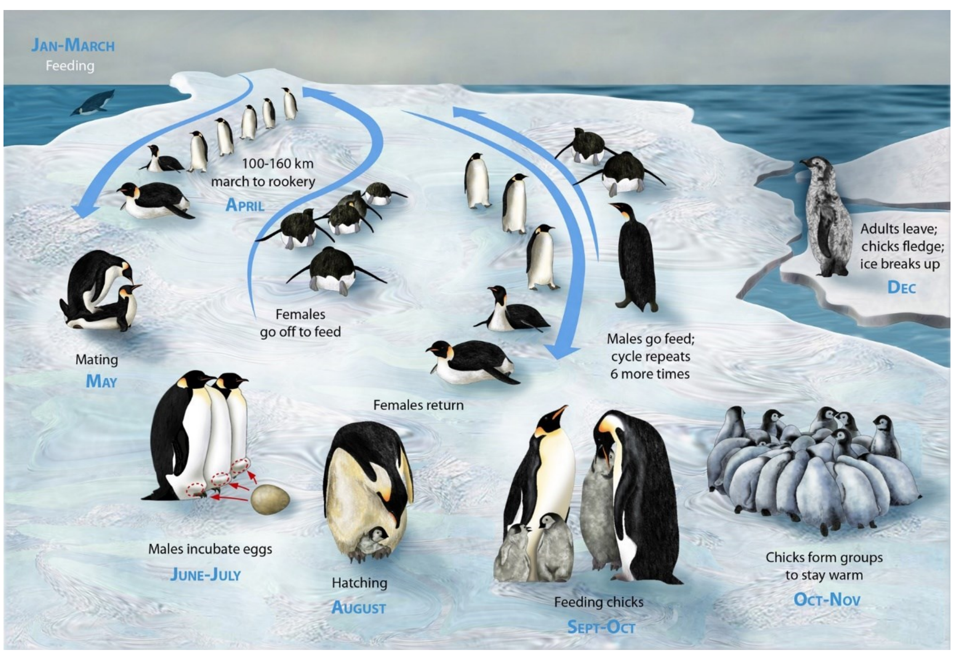


Figure 2.3. Emperor penguin breeding cycle. Timing can vary between sites. Adapted from Wienecke et al. 2013, in Trathan et al. 2020, p. 3.



Depiction of Emperor Penguin Breeding Behaviors (Photo Credit: Zina Deretsky, US Antarctic Program 1905)

Below is an outline of the emperor penguin breeding cycle with major events/milestones during each phase (Stonehouse 1953; Williams 1995; Wienecke 2011; Ainley et al. 2010; Kooyman et al. 2004; Gearheart et al. 2014; Jenouvrier et al. 2012; Trathan et al. 2020). See Appendix A for graphical depiction of breeding behavior.

1. Arrival at the colony – March-April
    - Annual sea ice begins to form. Arrival is highly synchronous at individual colonies, although arrival is later at more southerly colonies. Females remain at the colony from arrival to end of egg laying; males remain at the colony from arrival to end of incubation.

2. Courtship and Mating – April-May
    - No nest site or territory is defended, except immediately around each pair. Emperor penguins are monogamous during the breeding season, but mate fidelity is low between seasons (15%).

3. Egg Laying – May-June
    - The female always lays one egg. Post egg-laying, females leave to forage in the sea while the male incubates the egg.

4. Incubation – May-July
    - Incubation requires 60 days to complete. The male incubates the egg on its feet. The male does not eat for approximately 4 months after arriving at the breeding colony due to the time finding a mate upon arrival and then incubating the egg for 60 days. Penguins show remarkable tenacity while holding their eggs. However, birds deprived of their eggs may lose their incubation urge within a few hours and take on the characteristics of eggless birds. During this time, males survive on their own body fat. While incubating, males will form huddles in bad weather.

5. Hatching[1] – July-August
    - This is the coldest time in Antarctica. Males, who have been incubating chicks and fasting for approximately 4 months, feed the chick a protein-rich esophageal 'curd' secretion for the first few days prior to the return of the female with food. Females return to the colony around the time of hatching and take over chick-raising duties while the male then leaves to forage at sea. Securing a chick upon the female's return may be a random process and not a return to a specific partner, or they may find their mate vocally.

6. Chick Rearing – August-January
    - Adults guard the chicks for 25 percent (40–50 days) of the total chick-rearing period. Chicks rest on the adult's feet to maintain body temperature and protection from adverse weather and predation. The male and female take turns protecting the chick while the other goes out to sea to forage. When the chick is able to stand on the sea

[1] The mean hatching success (at Point Géologie colony) was 78 percent over a period of 16 years. Eggs lost from bad egg was 33 percent; eggs lost or displaced in huddle was 45 percent; egg broken during aggressive interactions was 10 percent. This data is based on 430 clutches (Williams 1995, p. 158).

ice unassisted, both adults need to forage at the same time to supply enough food for the chicks to develop properly and to feed themselves. Chicks will form huddles (crèche) to keep warm when both parents forage at sea. During the rearing phase, chicks grow a thick coat of down and develop rapidly.

7. Chicks Fledge[2,3] – December-January
   - It takes chicks a total of 150 days from birth to fledge and depart from the colony. Chicks increase their weight from about 315 grams at hatching to 1,810–2,550 grams at fledging, which is approximately 50 percent of adult weight. Chicks must have replaced their down with feathers (i.e., juvenile plumage) to survive at sea. Some adults leave earlier if they lost a chick, have not bred, or are too young to breed. Annual fast ice breaks out (see *Habitat*, below).

8. Adult Molting and Post-Molt Fattening – December-March
   - Adults forage at sea before molting (i.e., pre-molt fattening). They spend the off-season (i.e., austral summer) foraging in pack ice adjacent to open water to fatten, molt, and prepare for the next breeding season. Emperor penguins undertake a catastrophic molt between breeding seasons. They replace their entire plumage within about 30 days, are not waterproof during this time, and will die if they enter the ocean. Adults molt on the continent or nearby islands where it is accessible, on fast ice, or on consolidated pack ice (floes that normally drift with the ocean and wind, but which may merge and combine). Adults do not feed during molting and must have sufficient body reserves to molt successfully. When finished molting, emperor penguins are severely stressed energetically because they can lose up to half of their pre-molt body mass. Therefore, abundant prey is key to their survival. Once molting is complete, penguins forage at sea near their molting site before returning to the breeding colony to start the breeding cycle again

Breeding success appears to be highest in *Aptenodytes* species that rear on average 0.6–0.8 chicks per pair while laying only a single-egg clutch (Williams 1995, p. 33). Breeding success can vary from year to year in relation to both biotic factors (mainly food availability) and abiotic factors (e.g., ice conditions, heavy precipitation). At the Point Géologie colony (see Case Study, below), breeding success varied over six decades between 3–86% (Barbraud and Weimerskirch 2001, in Jenouvrier et al. 2012b, p. 31). It is unknown if the breeding success variability is a regional signal or affects the continent as a whole (Fretwell 2012, p. 7). Approximately 80 percent of mature emperor penguins breed every year (Barbraud and Weimerskirch 2001, p. 185). Age at first breeding is 5 years old for males and females (Mougin and Beveren 1979, in Williams 1995, p. 160).

Mean survival for adults was estimated at 95%, and mean survival for first-year penguins after fledging was 20% (Mougin and Beveren 1979, in Williams 1995, p. 160). Annual adult survival at Point Géologie was 60–98% over six decades (Barbraud and Weimerskirch 2001, in Jenouvrier et al. 2012b, p. 31). Population growth rate of long-lived species is mainly sensitive to changes in adult survival (Barbraud and Weimerskirch 2001, p. 184).

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[2] Fledging success ranged between 70–96% over 16 years at Point Géologie colony (Williams 1995, p. 158).
[3] Breeding success decreases substantially with early break out of fast ice (Williams 1995, p. 159).

Huddling Behavior at the Breeding Colony

Emperor penguins breed during harsh conditions (relative to other Antarctic seabirds) and are the only vertebrates that breed during the austral winter where they endure temperatures below negative 45°C (-49°F) and winds of 50 meters per second (112 mph) (Zitterbart et al. 2011, p. 1). One of their behavioral survival mechanisms in cold weather is to huddle together to reduce heat loss, which allows them to keep warm and decrease energy expenditure (Australian Antarctic Division 2020, unpaginated; Prevost 1961, in Croxall 1982, p. 179; Zitterbart et al. 2011, entire; Stonehouse 1953, p. 9).

Huddle structure is reorganized continuously to give each penguin a chance to spend sufficient time inside the huddle compared to time spent on the periphery (Zitterbart et al. 2011, p. 2). The penguins face the same direction and move in a highly coordinated manner while keeping the huddle packed (Prevost 1961, in Croxall 1982, p. 179; Zitterbart et al. 2011, p. 3). Individual penguins take small steps that travel as a wave through the entire huddle and over time, these small steps lead to large-scale reorganization of the huddle (Zitterbart et al. 2011, p. 2). In no other penguin species is this a normal part of adult behavior (Croxall 1982, p. 179). This huddling instinct means that they do not defend any territory. The emperor penguin is the only species of penguin that is not territorial (Australian Antarctic Division 2020, unpaginated).

Juveniles after Fledging

Juveniles stay at sea for 5 or 6 years before they return to the colony to mate (Woods Hole Oceanographic Institution 2019, p. 3; Williams 1995, p. 159). They disperse northward toward warmer waters and remain away from their colonies during post-natal dispersal (Thiebot et al. 2013, p. 542; Williams 1995, p. 159). Tagged juveniles from the Point Géologie and Cape Washington colonies initially moved far north beyond the line of latitude at 60 °S that marks the northern boundary of the Southern Ocean to reach open water areas and warmer waters to learn how to swim (Woods Hole Oceanographic Institution 2019, p. 2; Kooyman and Ponganis 2007, p. 1; Labrousse et al. 2019, entire). Once juveniles become more experienced at diving, they return south and back to the sea ice zone in autumn and winter (Labrousse et al. 2019, p. 5; Thiebot et al. 2013, p. 536). Juveniles spend the winter months making deeper dives within sea ice once they become more experienced at diving (Woods Hole Oceanographic Institution 2019, p. 2) and then prey upon other food resources like fish in deeper waters. Overall, juveniles survive and feed in heterogeneous habitats ranging from high sea ice conditions at higher latitudes to low sea ice conditions at lower latitudes (Labrrousse et al. 2019, p. 11).

Adults between Breeding Cycles

Adults feed to gain enough body reserves to molt between breeding cycles and successfully breed the next breeding season (see *Reproduction and Breeding Cycle*, above). Emperor penguins return to their breeding ground as early as ocean production in summer allows. They arrive sooner when higher summer ocean production allows them to rebuild their body reserves more rapidly and their reserves are sufficient to endure fasting at the colony at the beginning of the breeding season (Ancel et al. 2013, pp. 575–576).

A benefit of returning to the colony earlier may be predation avoidance, as adult emperor penguins do not have any predators on their breeding grounds (Ancel et al. 2013, p. 576). This may explain why emperor penguins spend more than half of the year on sea ice for breeding, molting, and resting – sea-ice being a safer place than in the water (Kooyman et al. 2004, p. 289; Ancel et al. 2013, p. 576). Another benefit of an early return to the colony may be that emperor penguins can increase their chances of finding a partner when arriving earlier at their breeding ground (Ancel et al. 2013, p. 576). Since they have no territory and no nest, partners often do not reunite and pairs are unstable from year to year. Courtship is the only time in the breeding cycle that allows both partners to be present at the colony at the same time and for a long time. Therefore, a longer courtship is likely to result in stronger pair bonds and may ensure better breeding success (Ancel et al. 2013, p. 576).

Emigration/Immigration (Dispersal)

Initially, it was suggested that movement or migration of emperor penguins between colonies is unlikely to be demographically important and modeling future population projections did not include movement of penguins between colonies (Jenouvrier et al. 2014, p. 716). Inter-colony dispersal was thought to be unlikely because of the unique breeding behavior of the species, colonies are inaccessible except during breeding, and cannot be encountered 'accidentally' while foraging during the nonbreeding season (Jenouvrier et al. 2014, p. 716). Additionally, emperor penguins were once believed to be philopatric, i.e., tending to return to or remain near a particular site or area (Cristofari et al. 2016, p. 5). However, recent research has demonstrated that emperor penguins move between breeding colonies that are largely open systems where dispersal is a fundamental mechanism (LaRue et al. 2015, p. 117; Cristofari et al. 2016, p. 5; Younger et al. 2017, pp. 3891–3895). Dispersal is expected to be common in unstable high-latitude environments (Cristofari et al. 2016, p. 5).

Dispersal for emperor penguin is composed of three stages: (1) species leaving the resident patch (emigration), (2) movement between patches, and (3) settling into a new patch (immigration) (Jenouvrier et al. 2017, p. 65). Breeding colonies may show positive or negative dispersal balance according to local habitat conditions (Cristofari et al. 2016, p. 5). For instance, environmental conditions driving the presence or absence of polynyas and their size may influence the relative rate of movement between colonies and cause a major uptick in emigration of birds away from sites less suitable in a particular breeding season (LaRue et al. 2015, p. 118). Dispersal may also be necessary due to sea ice instability. Dispersal allows emperor penguins to exploit the best breeding locations, although dispersal is not well understood for the species because they have only been marked at one site (Pointe Géologie colony in Terre Adélie) (Jenouvrier et al. 2017, p. 64; La Rue et al. 2015, p. 115).

Emperor penguin dispersal could include emigration to nearby but previously unknown colonies, which could partly explain the population decreases at Pointe Géologie and Haswell Island during the 1970s. At Pointe Géologie, unusually warm conditions was correlated with a decline in penguin abundance in the late 1970s (Barbraud and Weimerskirch 2001, p. 185). A similar situation likely occurred at Haswell Island (LaRue et al. 2015, p. 117). Additionally, emperor penguins at Halley Bay suffered from multiple years of breeding failure due to early break up of sea ice and have likely relocated to the Dawson-Lambert colony (Fretwell and Trathan 2019, p. 4). Moreover, glacial change can result in the relocation of a colony (i.e., Mertz Glacier) due to a calving event or a glacier retreating and exposing a colony to unfavorable weather conditions (LaRue et al. 2015, p. 118). Thus, it is important to try to distinguish between emigration to another colony or mortality because of the loss of habitat (LaRue et al. 2015, pp. 117–118).

Emperor penguins are known for their extraordinary migrations and travelling distances. Adults have travelled more than 2,000 km in the Ross Sea (Kooyman et al. 2004, p. 281) and a juvenile traveled 7,000 km in Terre Adélie (Theibot et al. 2013, p. 541). No gaps between emperor penguin colonies are greater than 500 km, except in front of large ice shelf fronts, which are probably areas of unsuitable habitat because of the disturbances associated with iceberg calving (see **Stressors**, below; Fretwell and Trathan 2020, p. 10). Therefore, a scenario in which all colonies are connected could be possible (Jenouvrier et al. 2017, p. 71). Because emperor penguins are known to disperse, recent research has included emigration and immigration as part of modeling efforts to characterize the adaptability of emperor penguins related to the risk of climate change affecting sea ice for which the species depends upon (Jenouvrier et al. 2017, entire) (see FACTORS AFFECTING THE SPECIES and FUTURE CONDITIONS, below).

Adaptations at Breeding Colonies

While the majority of breeding colonies occur on fast ice (see *Habitat*, below) around the continent, six breeding colonies have been observed to breed on permanently or annually located ice shelves rather than on fast ice. One occurs on rock, one occurs on or near a frozen lake, and two occur at offshore sites (Fretwell et al. 2014, p. 1; Ancel et al. 2017, p. 172; Fretwell and Trathan 2020, p. 4). Three of the colonies where penguins breed on ice shelves consist of marginal conditions of low mean sea ice extent and/or higher than average mean temperatures (Fretwell et al. 2014, p. 6). Local weather conditions can make sea ice highly variable in extent and duration, and therefore highly susceptible to regional changes. In contrast, ice shelves are less dynamic, and are less susceptible to local weather patterns (Fretwell et al. 2014, p. 2).

To breed on top of an ice shelf is a high-risk strategy. Large chunks of ice may calve off at any time, and depending on the timing and location of a calving event, emperor penguin may not be affected. However, if calving events occur near colonies while penguins are present, they could be crushed, trapped, or stranded and die of starvation, and abandon their chicks resulting in breeding failure (Kooyman et al. 2007, p. 1; Wienecke 2012, p. 1293). Additionally, breeding on land or on ice shelves would result in higher energy expenditure because of longer foraging trips and greater exposure to cold and wind on the top of the ice shelf (Wienecke 2012, p. 1293; Jenouvrier et al. 2014, p. 717).

It is unclear whether breeding on ice shelves is a new behavior associated with recent climate change and its effects on the presence of sea ice, or one that has always existed but not well documented (Fretwell et al. 2014, p. 2). Additionally, how penguins access ice shelves is unclear because emperor penguins are less agile on land, but perhaps they climb slopes when weather erodes the steepness of the shelf face or use ‘snow ramps’ (Fretwell et al. 2014, pp. 7–8; Zitterbart et al. 2014, p. 563). Snow accumulation may lead to a ramp that provides access to ice shelves (Wienecke et al. 2012, p. 1293).

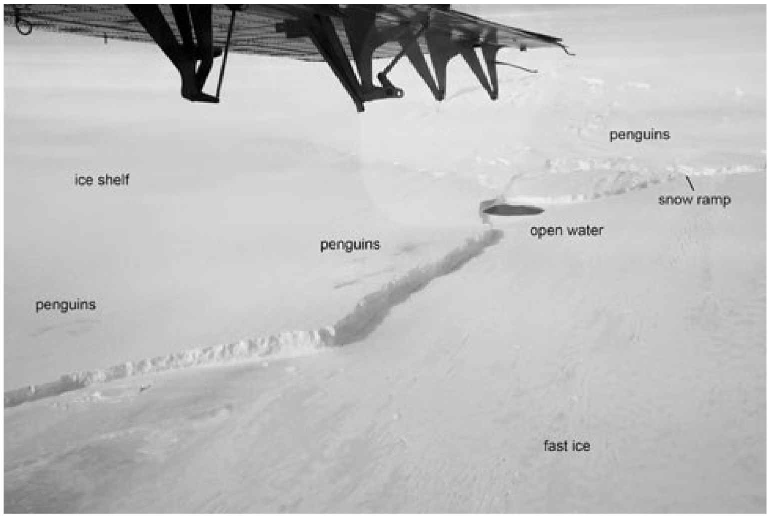

Figure 2.4. Emperor penguin on top of the West Ice Shelf (Wienecke et al. 2012, p. 1292)

Distribution

The Emperor Penguin is endemic to Antarctica and has a pan-Antarctic distribution, which means the species occurs around the entire continental coastline of Antarctica (see Figure 2.10 and Table 2 for breeding colony locations). The species breeds on sea ice between 66 °S and 78 °S latitude at the edge of Antarctic continent, Antarctic Peninsula, and adjacent islands (Williams 1995, p. 153; Fretwell and Trathan 2020, p. 7). There are no gaps larger than 500 km between colonies, except in front of large ice shelf fronts (Fretwell and Trathan 2020, p. 10; Figure 2.5).

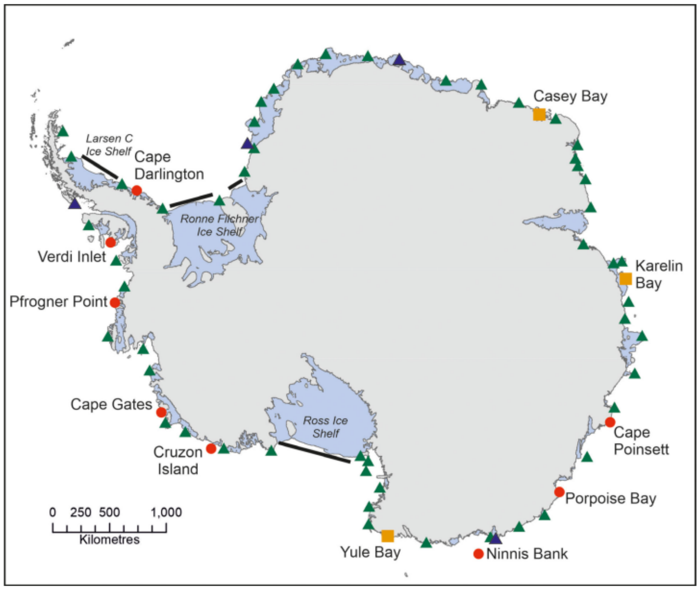

Figure 2.5. Newly discovered and rediscovered colonies found using Sentinel2 satellite imagery from 2016, 2018–2019. Newly discovered (red circles) and re-discovered (yellow squares) colonies, in relation to previously known colony locations (green triangles). The dark blue triangles are sites thought to no longer be extant. The only gaps in the distribution are in front of the largest three ice-shelves (Ross, Ronne-Filchner and Larsen C), marked as thick black lines, which are probably unsuitable habitat (Fretwell and Trathan 2020, p. 7).

Antarctica is in the Southern Ocean. The Southern Ocean extends from the coast of Antarctica to the line of latitude at 60 °S (NOAA 2020, unpaginated). The end of the Southern Ocean approximates at the extent of the Antarctic Convergence (or Atlantic Polar Front), where the cold Antarctic waters meet the warmer sub-Antarctic water. This acts as a biological barrier, making the Southern Ocean a largely closed system. The main surface currents are the Antarctic Circumpolar Current, which flows in an easterly direction encircling the Antarctic continent, and the east wind drift, which flows in a westerly direction, close to the Antarctic continent (Lutjeharms et al. 1985, in Collins and Rodhouse 2006, p. 192).

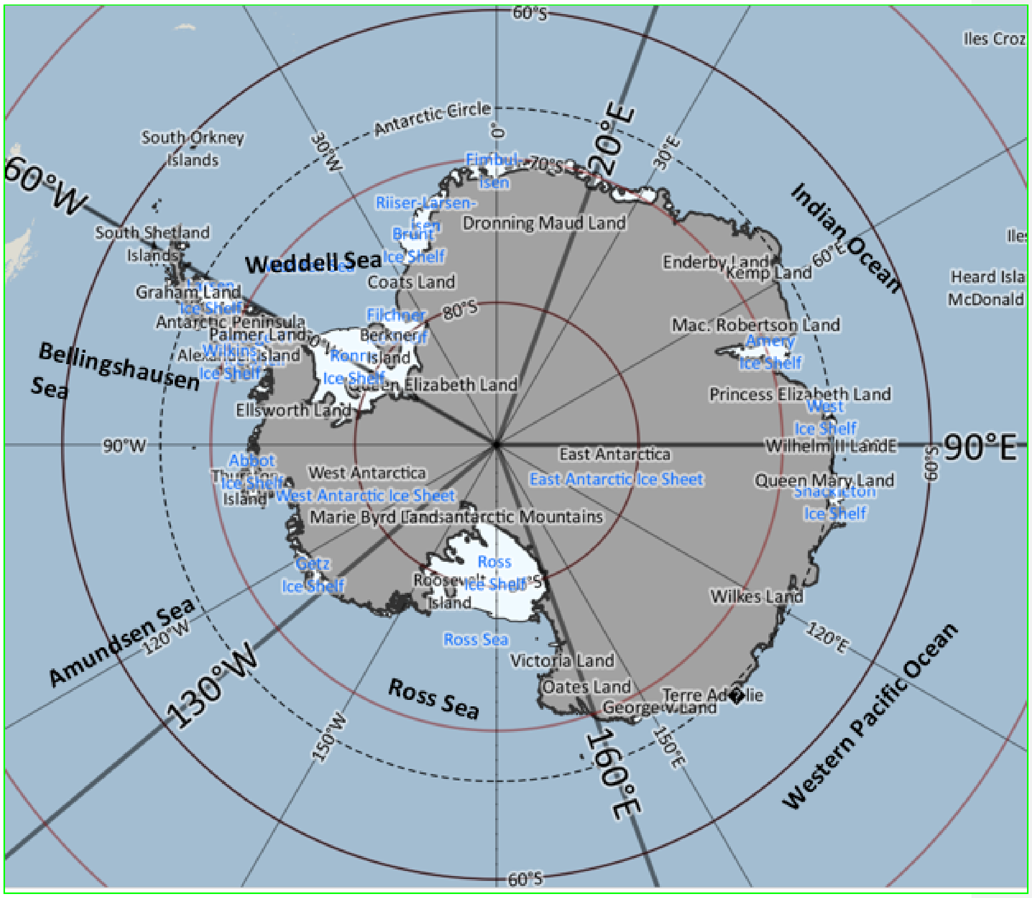

Figure 2.6. The Southern Ocean and Antarctica, showing major ice shelfs, names of land areas, and five sectors.

Literature regarding the emperor penguin’s distribution, the Antarctic continent, and the breeding colonies describe the continent and distribution in numerous ways. Colonies may also be described by the sea location in which they occur nearby (i.e., Weddell Sea, Bellingshausen Sea, Amundsen Sea, Ross Sea) or by the section of land on the continent (i.e., Dronning Maud Land, Enderby Land, or Terre Adélie (Figure 2.6). Much of the research on the historical trends in sea ice in the Southern Ocean and around the continent of Antarctica, and the potential effects of climate change on the Antarctic continent and emperor penguins, describes five sectors: Weddell Sea (60 °W–20 °E), Indian Ocean (20 °E–90 °E), Western Pacific Ocean (90 °E–160 °E), Ross Sea (160 °E–130 °W), and Bellingshausen-Amundsen Seas (130 °W–60 °W).

Species Needs

The emperor penguin needs annual sea ice to form breeding colonies; polynyas near breeding colonies to forage; food to forage year round and provide to growing chicks throughout the breeding season; the southern ocean to swim, forage, and disperse; and pack ice and/or ice floes to haul out and molt, rest, and avoid predation when not breeding.

Table 1. Species Needs for Life Stages of the Emperor Penguin

Life Stage	Resources needed for individuals to complete each life stage	Resource Function (BFSMD?)*	Information Source
Chicks	Sea ice	Developing, Molting	
	Fish, arthropods, crustaceans	F (provided by adults)	
Juvenile and Subadult	Sea ice	S, Molting	
	Fish, arthropods, crustaceans	F	
	Polynyas	F	
Adults	Sea ice	B, S, Molting	
	Fish, arthropods, crustaceans	F	
	Polynyas	F	

* B-breeding, F-feeding, S-shelter, M-migration, D-dispersal

Food and Feeding Behavior

Emperor penguins are near the top of the Southern Ocean's food chain (Australian Antarctic Division 2020, unpaginated). An adult penguin eats 2 to 3 kilograms (kg) per day, although when they need to fatten up before a molt or at the start of the breeding season, they can eat as much as 6 kg per day (Australian Antarctic Division 2020, unpaginated). During the breeding season, each pair of penguins consumes about one metric ton of food (Robertson and Newgrain 1996, in Cherel and Kooyman 1998, p. 335).

The diet of emperor penguins has mainly been investigated during the chick-provisioning period, when emperor penguins are most accessible to researchers (Trathan et al. 2020, p. 3). Emperor penguin has a varied menu that varies with time of year and location, and may vary at the same site between years (Trathan et al. 2020, p. 3; Williams 1995, p. 155). This indicates emperor penguin hunt opportunistically for available nektonic (animals that swim and migrate freely) and benthic (animals that live on the sea bottom) prey (Trathan et al. 2020, p. 3) and may shift foraging strategies relative to prey abundance and distribution. However, some prey items are more important, such as the Antarctic silverfish (*Pleurogramma antarctica*), which is always a main component of the diet and occupies all coastal regions of continental Antarctica (Cherel and Kooyman 1998, p. 335; Trathan et al. 2020, p. 3; Australian Antarctic Division 2020, unpaginated; Mintenbeck and Torres 2017, pp. 255–256).

Emperor penguin primarily consumes nototheniid fish, (which primarily consist of Antarctic and Sub-Antarctic fish), particularly Antarctic silverfish (Cherel and Kooyman 1998, entire, Williams 1995, p. 155). They also eat other fish, including, but not limited to, Antarctic jonasfish (*Notolepis coatsi*), bald rockcod (*Pagothenia borchgrevinki*) and rockcod species (*Trematomus* spp.), icefish species (*Chionodraco* spp.) and *Pagetopsis* spp.), and lanternfish (*Electrona antarctica*) (Cherel and Kooyman 1998, p. entire; Williams 1995, p. 156).

Other primary food sources are crustaceans, particularly Antarctic krill (*Euphausia superba*), and cephalopods such as glacial squid (*Psychroteuthis glacialis*) and Antarctic neosquid (*Alluroteuthis antarcticus*). Unlike fishes, the dietary importance of cephalopods (squid) and crustaceans (krill) varies according to locality (Cherel and Kooyman 1998, p. 335). Most prey items are small but emperor penguins also consume a few specimens of larger size (Cherel and Kooyman 1998, p. 341).

Prey composition suggests two different feeding strategies: shallow dives exploring the rugged underside of sea ice where krill is consumed, and deep dives where fish and squid are consumed (Klages 1989, p. 389; Labrousse et al. 2019, pp. 6–12; Williams 1995, p. 155). The predominance of pelagic species (species that occupy the water column) in food samples agrees well with the diving behavior of emperor penguin (Cherel and Kooyman 1998, p. 342; Williams 1995, p. 155). The majority of dives are less than 200 meters (m), with many at 20 to 180 m (Kooyman and Kooyman 1995, p. 539; Kirkwood and Robertson 1997, in Cherel and Kooyman 1998, p. 342). These dives occur in mid-water, where penguins probably feed on krill and Antarctic silverfish, which both form dense swarms at these depths (Lomakina 1966 and Gon and Heemstra 1990, in Cherel and Kooyman 1998, p. 342). They also dive deeper, below 200 m, and target larger fish and squid where krill are less abundant (Cherel and Kooyman 1998, p. 342).

Dives up to 500 m, with the deepest recorded dive to 565 m, allows them to forage in the whole water column over the Antarctic shelf (Cherel and Kooyman 1998, p. 335). Deeper dives likely are related to the depth of the thermocline (a steep temperature gradient in water marked by a layer above and below which the water is at different temperatures) and the seasonal change in the distribution of their prey – krill and other fish (Woods Hole Oceanographic Institution 2019, p. 2; Labrousse et al. 2019, p. 1). On average, dives last 3 to 6 minutes but the longest dive on record was 22 minutes (Australian Antarctic Division 2020, unpaginated). Shallow dives (less than 20 m) are very common, which are interpreted as non-foraging dives, traveling dives, or recovery from oxygen debt (Cherel and Kooyman1998, p. 342).

Habitat

Emperor penguins mainly occur on level areas of stable sea (fast) ice, close to the coast or up to 18 km offshore, and amongst closely packed grounded icebergs that prevent ice breaking out during the breeding season and shelter from the wind. These sites are often sheltered in the lee of ice cliffs, hills, or icebergs and most colonies are near polynyas (Williams 1995, p. 155; Kooyman 1993, p. 147).

Sea Ice

Emperor penguins depend upon stable sea ice throughout their breeding season to raise chicks (Williams 1995, pp. 157–159; Trathan et al. 2020, p. 3). Sea ice is any form of ice found at sea that has originated from the freezing of seawater. Sea ice can remain in place for months or years, locked in place by capes, islets, or grounded icebergs, in which case it is called fast ice (Ainley et al. 2010, p. 51). Fast ice is fastened to the shore or ocean bottom, typically over shallow ocean shelves at continental margins and ~~is defined by the fact that~~ it does not move with the winds or currents (National Snow and Ice Data Center (NSIDC) 2020, unpaginated; Ainley et al. 2010, p. 51). Only during extended periods of calm and cold temperatures can fast ice thicken sufficiently (approximately 2 m) that it no longer is susceptible to being blown loose by wind (Ainley et al. 2010, p. 52). Winds increase the extent of sea ice, the size of coastal polynyas, and decrease ice thickness (Ainley et al. 2010, p. 53). Sea ice broken into pieces and not attached to the shoreline is called an ice floe~~s~~ or pack ice as it drifts in response to winds, currents, or other forces (Ainley et al. 2010, p. 51; National Snow and Ice Data Center 2020, unpaginated). Sea ice concentration, extent, and quality will vary in response to both long-term changes in climate and short-term phenomena such as storm systems and seasonal wind patterns (Liu et al. 2004, p. 3, Fraser et al. 2012, in LaRue et al. 2015, p. 117).

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Blanketing millions of square kilometers, sea ice forms and melts with the polar seasons. The annual growth and melt of Antarctic sea ice is the largest seasonal ice growth and melt cycle on the planet (Eayrs et al. 2019, p. 1057). Winter sea-ice expansion is limited by the influence of the Antarctic Circumpolar Current. This current is the most important current in the Southern Ocean, and the only current that flows completely around the globe. As it encircles the Antarctic continent, it flows eastward through the southern portions of the Atlantic, Indian, and Pacific Oceans (Smith et al. 2013, unpaginated).

Sea ice varies substantially during the austral seasonal cycle and from one year to the next (i.e., inter-annual variability) (Zwally 2002, p. 9-8). Inter-annual variability is illustrated by the contrast between a high sea ice extent in September (of a given year) followed the next summer by a high or low sea ice in February (Parkinson 2019, p. 14414). Sea ice in the Southern Ocean and within all five sectors is generally at its minimum amount in February and maximum amount in September (Parkinson 2019, pp. 14414–14415; Figure 2.7).

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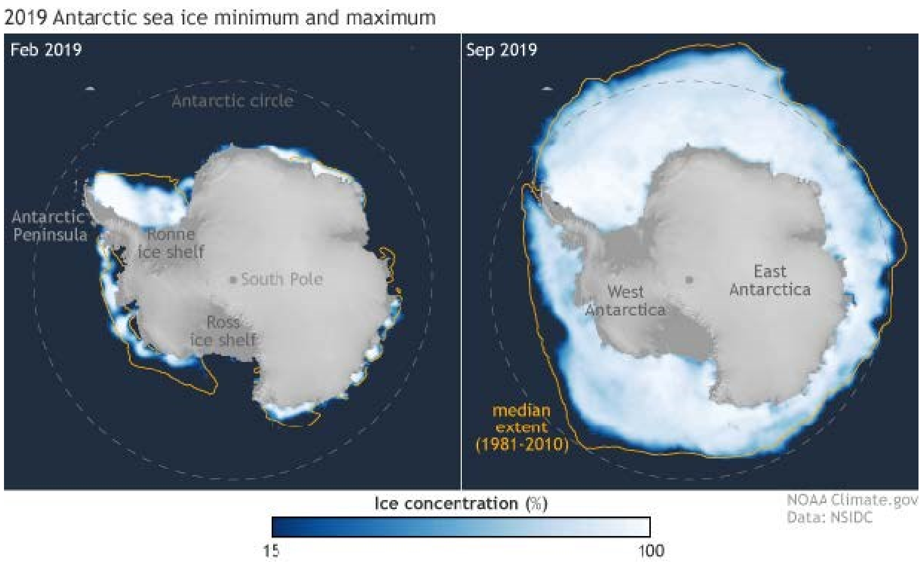

Figure 2.7. Sea ice minimum in February and maximum in September 2019 (NSIDC 2020, unpaginated).

Forty years (1979–2018) of sea ice in the Southern Ocean and within the five sectors has been analyzed using a satellite-based multichannel passive-microwave data record (Parkinson 2019, p. 14414). This method has advantages for studying ~~over other data to study~~ changes in the extent and distribution of sea ice because it allows monitoring every 1 or 2 days, data goes back to the 1970s, imaging differentiates between sea ice and liquid water and can be made irrespective of day or night conditions, and ~~data travels through most cloud covers~~it is minimally impacted by cloud cover (Parkinson 2019, p. 14414).

The monthly and yearly averages of sea ice data were analyzed using data for each day that data were available (Parkinson 2019, p. 14414). Sea ice extent was calculated by summing up grid cells (25km by 25km) that had at least 15 percent sea ice concentration (Parkinson 2019, p. 14414). Fifteen percent cover is used because it is difficult to distinguish ice from open water at lower ice concentrations using satellite imagery (Parkinson 2002, p. 437, Zwally et al. 2002, p. 9-4; NSIDC 2020, unpaginated). All datasets are from the National Snow and Ice Data Center (Parkinson 2019, p. 14414).

The vast majority of breeding colonies around the continent occur on fast ice (Fretwell et al. 2014, p. 1; Trathan et al. 2020, p. 3). Emperor penguins are too clumsy to climb over high jumbles of rocks or broken sea ice. They need sea ice of a low freeboard—the difference between the height of sea ice and water—that is not more than a few tens of centimeters to exit the sea and return to land (Ainley et al. 2010, p. 53; Fretwell et al. 2014, p. 1; Trathan et al. 2011, p. 1). However, a very few colonies exist temporarily or permanently on ice shelves.

As fast ice is forming and thickening, the breeding season for the species begins in the austral fall (March-April) and continues through to the following mid-summer (December-January) (see *Reproduction and Breeding Cycle*, above). For emperor penguins to breed successfully, sea ice needs to be stable long enough for the chicks to molt from downy plumage to waterproof plumage in order to survive at sea (Yale Climate Connections 2020, unpaginated). Sea ice breaking up before chicks molt will result in high chick mortality because chicks will drown and die (Fretwell et al. 2014, p. 1).

Emperor penguins prefer ideal sea ice conditions (Yale Climate Connections 2020, unpaginated; Jenouvrier et al. 2014, p. 715). Too much sea ice reduces adult survival and breeding success because it requires longer foraging trips, higher parental energy expenditure, and reduces chick-provisioning (Jenouvrier et al. 2012, p. 2764). On the contrary, high sea ice positively affects adult survival by increasing food availability (Barbraud and Weimerskirch 2001, p. 185). Not enough sea ice reduces adult survival and breeding success, decreases space for molting, a~~e~~ffects the food web resulting in lower food resources, and/or not enough protection from predators (Yale Climate Connections 2020 unpaginated; Jenouvrier et al. 2012, pp. 2764–2766). Males have reduced survival compared to females because males are more constrained energetically due to longer fasting periods during the breeding season (Jenouvrier et al. 2012, p. 2760).

Polynyas

Polynyas are key biophysical features of the Antarctic ecosystem (Labrousse et al. 2019, p. 2). Polynya formation is driven by either upwelling of circumpolar deep water or by the outflow of katabatic winds[4] that push sea ice away from the coastline (Martin 2001, in Younger et al. 2015, p. 2216). Polynyas are prime foraging habitat with high abundance of food resources as open water areas are associated with high rates of primary production (Labrousse et al. 2019, p. 2; NSIDC 2020, unpaginated). Almost all breeding colonies occur near polynyas (Trathan et al. 2020, p. 3; Nihashi and Ohshima~~i~~ 2015, p. 3657; see Figure 2.8). They provide the closest open water to a colony and reduce commuting time and energy expenditure between a breeding colony and food supply, particularly when fast ice extends far from colonies (Younger et al. 2015, p. 2216; Ainley et al. 2010, p. 54). Some polynyas are permanent features of the sea ice zone and create areas of hyper-productivity, such as the Ross Sea polynya, while most are smaller and ephemeral features depending on wind stresses and currents (Younger et al. 2015, p. 2216).

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[4] Katabatic winds form by cold dense air flowing out from the polar plateau of interior Antarctica and down the steep vertical drop along the coast as cold air rushes over the land mass (UW-Madison 2020, unpaginated).

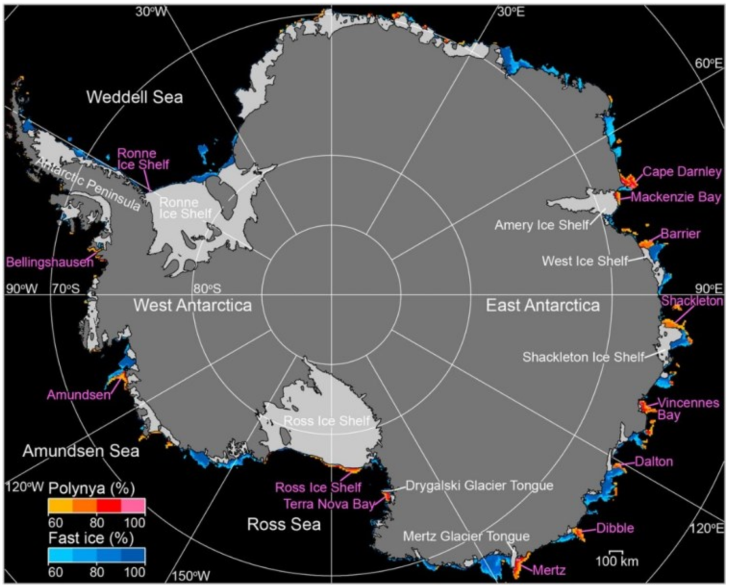

Figure 2.8. Antarctica coastal polynyas and fast ice. Color shadings show frequency of occurrence during the freezing period (March–October) for the period 2003–2011. Continent is dark gray and ice shelves and glacier tongues are light gray (Nihashi and Ohshima 2015, p. 3657).

Shelter

Breeding colonies are often located in areas where icebergs and ice cliffs shelter them from the prevailing winds (Figure 2.9; Prévost, 1961; Kooyman, 1993, p. 144; Kooyman et al. 2007, p. 35). Grounded icebergs can prevent ice breaking out during the breeding season and allow colonies to develop in the lee of ice cliffs (Williams 1995, p. 155). Strong wind may cause ice to break up, destroy the colony for that year, and force adults to abandon their chicks in order to survive (Kooyman 1993, p. 147).

Figure 2.9. Emperor penguin colony at Beaufort Island. Photo taken in 2018. Photo credit: Mike Lucibella, National Science Foundation (US Antarctic Program 2020, unpaginated).

Population

While the species was recognized as a distinct species in 1844, the first colony was discovered in 1902 at Cape Crozier (in the Ross Sea) (Wilson 1907, p. 3; Wienecke 2011, p. 1). Until 1954, only four colonies were known, and an increasing number of colonies were discovered with the establishment of permanently occupied research stations (Wienecke et al. 2013, p. 26). The use of modern technology, specifically satellite imagery, has increased knowledge of the total population size, population size at each colony, and distribution of colonies around Antarctica for the entire species' range.

As of 2020, 50 of the 54 colonies previously reported were extant, eight new colonies were discovered, and three colonies were rediscovered. Therefore, there are 61 known emperor penguin breeding colonies (Table 2 and Figure 2.10; Fretwell and Trathan 2020; Fretwell and Trathan 2009; Fretwell et al. 2012, 2014; Wienecke 2011; Ancel et al. 2014; LaRue et al. 2015). The total population estimate was approximately 260,000 breeding pairs or about 600,000 birds (Trathan et al. 2020, p. 4; National Geographic 2020, unpaginated). The recent discovery of new colonies increases the number of colonies by almost 20 percent and is estimated to increase the total population 5 to 10 percent (approximately 25,000–55,000; 10,000–22,000 breeding pairs) (Fretwell and Trathan 2020, p. 10).

Data sources include ground and aerial surveys and particularly satellite imagery. In the absence of direct measurements of breeding adults, chick counts may be used to detect large changes in the breeding populations of emperor penguins because each pair only breed once per year and lay only one egg (Barber-Meyer 2008, p. 9). If sites are observed throughout the breeding season, or at least during the chick-rearing period (August–December), and are visible in approximately the same place in multiple years, it is likely they are breeding sites (Fretwell and Trathan 2020, p. 10).

Most of the colonies have never been, and probably never will be visited by humans because most breeding colonies are impossible to visit. They are too remote from occupied research stations and the emperor penguin breeding season occurs during the austral winter (Jenouvrier et al. 2014, p. 715; Ancel et al. 2014, p. 1). Therefore, satellite imaging is a valuable method for monitoring inaccessible colony locations and allows estimates of populations at colonies by differentiating between penguins, shadows, and guano (seabird excrement) (Ancel et al. 2014, p. 2; Barber-Meyer et al. 2007, pp. 1566–1567). Additionally, satellite imagery is less costly than aerial or ground censuses when the objective is to document presence and/or absence or changes in population sizes (Barber-Meyer et al. 2007, p. 1569).

Although offering a major advance since it allows a global imaging of emperor penguin colonies, satellite imaging may miss certain colony locations when challenged by certain features of polar ecosystems, such as snow cover, evolving ice cover, cloud cover, and rapidly changing habitat (Ancel et al. 2014, pp. 1, 5). Despite these challenges, the use of satellite technology and the discovery of new colonies has enabled a revised estimate of total population distribution and size (Trathan et al. 2020, p. 4). To have more confidence in satellite observations, a multi-temporal/multi-year approach is used to ensure that breeding sites are not missed due to heavy snowfall, deep shadows or topographic features such as ice cliffs (Ancel et al. 2014, p. 5).

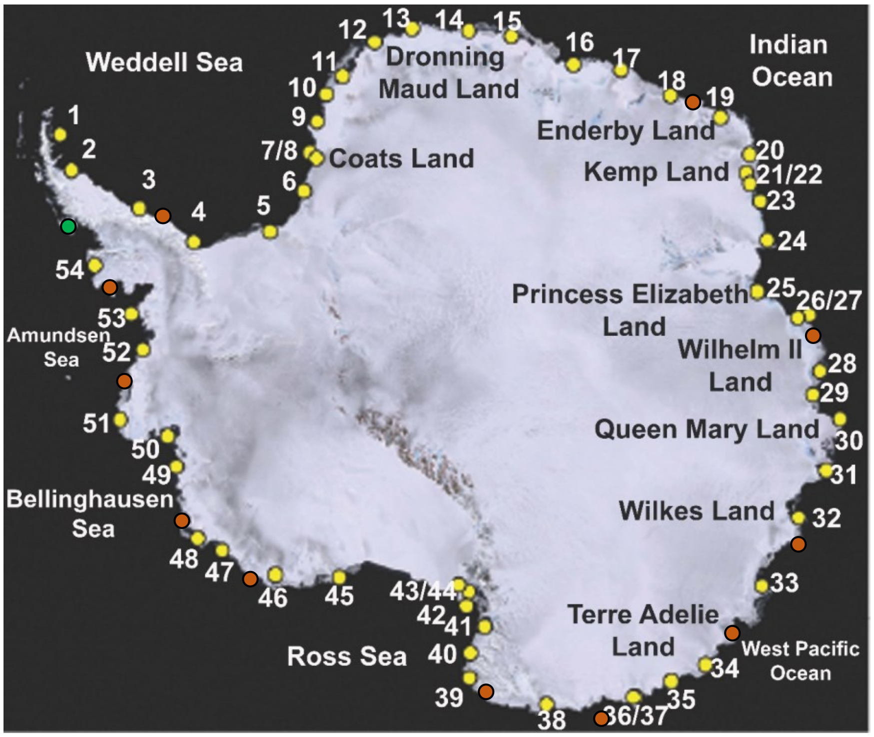

Figure 2.10. Distribution of 54 known emperor penguin breeding colonies (as of 2020; yellow dots and numbered), which includes 4 colonies that were not extant in 2019 (7, 15, 18, 37) and the extirpated Dion Islets colony with approximate location (green dot). The orange dots with approximate locations are 11 colonies that have been discovered or rediscovered in 2020 (see Table 2; Jenouvrier et al. 2019b, p. 2; Fretwell and Trathan 2020, p. 7).

Table 2. Emperor penguin breeding colony names (Fretwell and Trathan 2020). The colony numbers relate to Figure 2.10, above. Population size estimates from Trathan et al. (2019).Latitude, longitude, and notes (Ancel et al. 2017; Fretwell and Trathan 2020). New colonies discovered, habitat type, and notes (Table 3; Fretwell and Trathan 2020).

Colony Name	Colony No.	Sector	Latitude	Longitude	Population Size 2019	Habitat Type	Notes
Snow Hill	1	Weddell Sea	-64.524	-57.445	2000-4000	A	
Jason Peninsula (Larsen Ice Shelf)	2		-66.100	-60.674	0-2000	E	
Dolleman Island	3		-70.611	-60.421	2000-4000	A	
Smith Peninsula	4		-74.369	-60.827	2000-4000	A	
Gould Bay	5		-77.710	-47.656	4000-8000	A	No longer in Gould Bay
Luitpold Coast	6		-77.271	-33.552	4000-8000	D	
Halley Bay	7		-75.555	-27.423	8000-12000	A	Not extant in 2019
Dawson-Lambert Ice Tongue	8		-76.014	-26.648	12000-16000	A	
Stancomb-Wills Glacier	9		-74.120	-23.087	4000-8000	A	
Drescher Inlet	10		-72.826	-19.326	8000-12000	C	
Riiser Larsen Ice Shelf	11		-72.124	-15.106	8000-12000	D	
Atka Bay/Atka	12		-70.614	-8.132	4000-8000	A	
Sanae	13		-69.999	-1.413	2000-4000	C	Located in new position
Astrid Coast Ice Tongue	14		-69.948	8.318	0-2000	A	
Lazarev Ice Shelf/Lazarev	15		-69.750	15.548	0-2000	A	Not extant since 2014
Ragnhild Coast	16	Indian Ocean	-69.908	27.155	4000-8000	C	
Gunnerus (Riiser Larsen Peninsula)	17		-68.762	34.382	4000-8000	A	
Umbeashi Rock (Umebosi)	18		-68.046	43.017	0-2000	A	Extremely small and not visible in 2019
Amundsen Bay	19		-66.783	50.544	0-2000	F	
Kloa Peninsula/Point	20		-66.641	57.278	2000-4000	A	

Fold Island	21		-67.324	59.316	0-2000	B	
Taylor Glacier	22		-67.454	60.878	0-2000	F	
Auster	23		-67.397	63.974	4000-8000	D	
Cape Darnley	24		-67.887	69.696	2000-4000	A	
Amanda Bay	25		-69.271	76.835	4000-8000	AB	
Barrier Bay	26		-66.550	81.818	0-2000	E	
West Ice Shelf	27		-67.225	81.931	0-2000	A	
Burton Ice Shelf	28		-66.272	89.695	0-2000	D	
Haswell Island	29	Western Pacific Ocean	-66.531	93.008	2000-4000	B	
Shackleton Ice Shelf	30		-65.089	96.020	4000-8000	E	
Bowman Island	31		-65.161	103.067	0-2000	D	
Petersen Bank	32		-65.918	110.235	2000-4000	D	
Sabrina Coast	33		-66.177	121.058	0-2000	D	
Dibble Glacier	34		-66.000	134.800	12000-16000	A	
Pointe Géologie	35		-66.674	140.005	2000-4000	B	
Mertz Glacier	36		-67.240	145.535	2000-4000	C	
Mertz Glacier East (Break Off)	37		-67.366	145.834	4000-8000	B	Not extant, reunited with Mertz Glacier
Davis Bay	38		-69.348	158.492	0-2000	A	
Cape Roget	39	Ross Sea	-71.988	170.597	8000-12000	A	
Coulman Island	40		-73.348	169.624	16000+	A	
Cape Washington	41		-74.637	165.382	8000-12000	A	
Franklin Island	42		-76.187	168.440	4000-8000	A	
Beaufort Island	43		-76.925	167.043	0-2000	A	
Cape Crozier	44		-77.465	169.329	0-2000	C	
Cape Colbeck	45		-77.135	-157.730	16000+	A	
Rupert Coast	46		-75.382	-143.308	0-2000	E	
Ledda Bay	47		-74.272	-131.243	0-2000	A	Most years ice breaks up early

Mount Sipple (Thurston Glacier)	48	Bellingshausen-Amundsen Seas	-73.498	-125.620	2000-4000	A	
Bear Peninsula	49		-74.350	-110.239	8000-12000	A	
Brownson Islands	50		-74.351	-103.631	4000-8000	B	
Noville Peninsula	51		-71.769	-98.447	2000-4000	A	
Bryan Coast	52		-73.249	-85.348	0-2000	A	
Smyley Island	53		-72.302	-78.819	2000-4000	A	
Rothschild Island	54		-69.521	-72.229	0-2000	AB	
Dion Islets			-67.866	-68.704	Extirpated		Considered extirpated but 2–3 chicks recently reported
Additional Colonies Discovered/Rediscovered (Fretwell and Trathan 2020)							
Cruzen Island			-74.724	-140.357	Not reported	A	Discovered
Cape Gates			-73.661	-122.697	Not reported	A	Discovered
Pfrogner Point			-72.569	-89.906	Not reported	E	Discovered
Verdi Inlet			-71.556	-74.760	Not reported	A	Discovered
Cape Darlington			-71.887	-60.134	Not reported	E	Discovered
Karelin Bay			-66.412	85.384	Not reported	A	Rediscovered*
Cape Poinsett			-65.782	113.235	Not reported	A	Discovered
Porpoise Bay			-66.320	129.750	Not reported	A	Discovered
Ninnis Bank			-66.723	149.677	Not reported	D	Discovered
Yule Bay			-70.716	166.478	Not reported	A	Rediscovered
Casey Bay			-67.312	46.957	Not reported	A	Rediscovered
Total Population					**≈270,000–280,000 breeding pairs; 625,000–650,000 total birds**	**A total of 66 breeding colonies ever known. 50 extant in 2019 + 11 colonies discovered/rediscovered = 61 extant colonies in 2020**	

*rediscovered colonies were previously reported before the era of high-resolution satellite imagery was available

Table 3. Description of habitat types (Fretwell and Trathan 2020, p. 3).

Breeding habitat: Emperor penguin breeding locations can be classed into four groups based on geographic features	
A	The windward side of bays, headlands, glacier tongues and ice shelves. This is the most common location for colonies. Over half of all known colony (30 of 54) show this preference
B	Land-fast ice within small island archipelagos. Five colonies, with a further two that also conform with group A, have this characteristic.
C	Semi-permanent ice creeks. Five colonies, mostly around Dronning Maud Land, share this trait
D	Offshore on fast ice amongst icebergs trapped by shallow shoals. Seven colonies have this location preference. Two such colonies in the eastern Weddell Sea are less than 10 km offshore, but two such colonies in East Antarctica: Burton Ice Shelf and Sabrina Coast are over 50 km from land.
Some colonies use geographic features that are more challenging to search	
E	Ice shelf breeders. Four colonies have regularly been located on ice shelves (Fretwell et al. 2014)
F	Land. One colony breeds entirely on land (Robertson et al. 2014), another has been found on a frozen lake, but whether this is the regular location of the breeding colony is difficult to assess due to lack of ground survey (Kato 1999).

Population and Species Needs for Viability

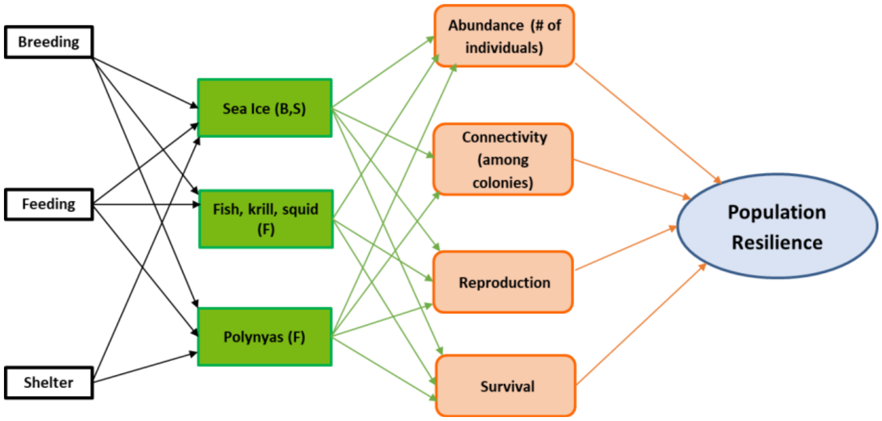

Figure 2.11. Factors that contribute to the emperor penguin's viability. These include habitat (sea ice; fish, krill, squid; and polynyas) and demographic variables (abundance, connectivity, reproduction, survival).

Viability is the ability of a species to maintain populations in the wild over time. To assess viability, we use the conservation biology principles of resiliency, redundancy, and representation (the 3Rs; Shaffer and Stein 2000, pp. 308–311). To sustain populations over time, a species must have the capacity to withstand:

1. Environmental and demographic stochasticity and disturbances (Resiliency)
2. Catastrophes (Redundancy),and
3. Novel changes in its biological and physical environment (Representation).

A species with a high degree of resiliency, redundancy, and representation is better able to adapt to novel changes and to tolerate environmental stochasticity and catastrophes. In general, species viability will increase with increases in resiliency, redundancy, and representation (Smith et al. 2018, p. 306).

Resiliency, Redundancy, and Representation

Resiliency is the ability of a species to withstand environmental stochasticity and recover from periodic disturbances. Resiliency is measured by abundance, population growth rate, and other demographic factors. Factors influencing the ability of emperor penguin to withstand environmental variation include population abundance (i.e., breeding pairs) at each colony and rangewide, and the sea ice condition (habitat) during each breeding season. Prey abundance influences emperor penguin resiliency and is tied to sea ice extent and duration. Thus, sea ice condition is a good proxy to account for prey conditions at emperor penguin breeding colonies.

For the emperor penguin to withstand environmental variation, and maintain viability, the species must maintain multiple resilient breeding colonies. Sea ice can be highly variable annually; therefore, emperor penguins may move to more suitable or higher quality habitat if sea ice at a certain location is not adequate for breeding. Dispersal allows the penguins to exploit the best breeding locations, although dispersal is not well understood for emperor penguin.

Redundancy is the ability of a species to withstand catastrophic events and is measured by the number and distribution of populations or occurrences across representative areas. Redundancy protects a species against the unpredictable and highly consequential events for which adaptation is unlikely. In short, it is about spreading the risk. This reduces the likelihood that all populations or occurrences would be affected by any single event simultaneously. Given sufficient redundancy, single or multiple catastrophic events are unlikely to cause extinction of a species. It follows then that greater redundancy may lead to better overall viability. For emperor penguin to have sufficient redundancy and the entire species not be affected by a catastrophic event, the species must maintain multiple resilient breeding colonies located around the continent of Antarctica.

Representation is the ability of a species to adapt or evolve to changing physical and biological conditions. Representation is measured by the variation across the species including both the genetic diversity and ecological diversity of a species. Genetic diversity is the number and frequency of unique alleles within and among populations. Ecological diversity is the physiological, ecological, and behavioral variation exhibited by a species across its range. Emperor penguins consists of at least four known metapopulations and dispersal within and among the colonies within these metapopulations provides gene flow. Therefore, the species needs to maintain multiple resilient colonies within and outside of the known metapopulations to have some degree of connectivity among colonies within the five sectors.

Additionally, most colonies occur on fast ice. It is unknown whether the few colonies that breed on ice shelves is a new adaptive behavior associated with climate change and its effects on sea ice at certain colonies or one that has always existed but not well documented. The adaptive capacity of emperor penguins is unknown, but the species has so far shown little evidence of adaptive capacity.

CHAPTER 3: FACTORS AFFECTING THE SPECIES

One major threat affects the entire population of emperor penguin and each breeding colony now and into the future – a changing climate affecting the extent and duration of sea ice and relatedly prey abundance around the continent of Antarctica. Additionally, ocean acidification because of climate change is projected to affect the Southern Ocean ecosystem. Minor anthropogenic stressors on the emperor penguin include tourism, contaminants, and krill fisheries but these minor effects are not thought to be driving factors of the emperor penguin's viability.

Climate Change

The climate system is a~~the~~ highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere and the interactions between them. Climate change is a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades (i.e., 30 years) or longer. Climate change may be due to natural internal processes or external forcings[5], or to persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC 2014a, p. 120).

The Earth's climate has changed throughout history. Substantial regional variation exists in observation and projections of climate change impacts because the impacts themselves vary and because of unequal research attention (IPCC 2014b, p. 1137). However, the current warming trend is significant because most of it is extremely likely to be the result of humans adding heat trapping greenhouse gases to the atmosphere (IPCC 2014a, p. 5; NASA 2020; NCTC 2017; IPCC 2014a, p. 4). Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, largely because of economic and population growth. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years (IPCC 2014a, p. 4). The planet's average surface temperature has risen about 0.9 degrees Celsius (°C; 1.62 degrees Fahrenheit) since the late 19th century – most of the warming occurred in the past 35 years, with the six warmest years on record taking place since 2014 (NASA 2020, unpaginated).

The consequences of a changing climate are difficult to predict, but certain effects seem likely. The atmosphere and ocean are warming, the amounts of snow and ice are diminishing, and sea level is rising (NASA 2020, unpaginated; IPCC 2014a, p. 2). A ~~and a~~ll three of these patterns are predicted to continue. Table 4 shows the difference in global mean surface air temperature under the 'low' climate change scenario of Representative Concentration Pathway (RCP) 2.6, 'moderate' scenario of RCP 4.5, and 'business as usual' scenario of RCP 8.5; and the sea surface temperature, and surface pH under RCPs 2.6 and 8.5.

The magnitude of climate change into the future depends primarily on the amount of heat-trapping gases emitted globally, how sensitive the Earth's climate is to those emissions, as well as any human responses to climate change by developing adaptation and mitigation policies (NASA 2020, unpaginated; IPCC 2014a, p. 17). Table 4 shows the projected increase in global mean surface temperature and ocean variables for near-term and end of century relative to the recent past 1986–2005). *The 5–95% range is the likely range (IPCC 2019b, p. 46).Sea surface temperature and pH were not calculated for RCPs 4.5 or 6.0.

Table 4. Comparison of global surface temperature and ocean variables between RCPs 2.6, 4.5, 6.0, and 8.5 (IPCC 2019b, p. 46).

		Near-term 2031–2050		End of Century 2081–2100	
	Scenario	**Mean**	**5–95% Range***	**Mean**	**5–95% Range***
Global Mean Surface Air Temperature (°C)	RCP 2.6	0.9	0.5–1.4	1.0	0.3–1.7
	RCP 4.5	1.1	0.7–1.5	1.8	1.0–2.6
	RCP 6.0	1.0	0.5–1.4	2.3	1.4–3.2
	RCP 8.5	1.4	0.9–1.8	3.7	2.6–4.8

[5] External forcing refers to a forcing agent outside the climate system causing a change in the climate system (IPCC 2014, p. 123)

Global Mean Sea Surface Temperature (°C)	RCP 2.6	0.64	0.33–0.96	0.73	0.20–1.27
	RCP 8.5	0.95	0.60–1.29	2.58	1.64–3.51
Surface pH (units)	RCP 2.6	-0.072	-0.072–-0.072	-0.065	-0.065–-0.066
	RCP 8.5	-0.108	-0.106–-0.110	-0.315	-0.313–-0.317

The Polar Regions (Arctic and Antarctica) will be profoundly different in the future compared with today, the degree of which will depend strongly on the rate and magnitude of global climate change (Meredith et al. 2019, p. 206). Important differences in the physical setting of the two Polar Regions guide the nature and magnitude of interactions of cryosphere (the frozen water part of the Earth system) and ocean systems and their global linkages. The Arctic is an ocean surrounded by land and the Antarctic is a continent surrounded by an ocean (Meredith et al. 2019, p. 209).

Commented [HZ5]: How does this statement relate to the previous one, i.e. why specifically is this information important in the context of this report?

The Antarctic continent has seen less uniform temperature changes over the past 30–50 years and most of Antarctica has yet to see dramatic warming (Meredith et al. 2019, p. 212). The Antarctic Peninsula juts out into warmer waters north of Antarctica and is one of the fastest warming places on Earth, warming 2.5 °C (4.5 °F) since 1950. In East Antarctica, no clear trend has emerged, although some stations appear to be cooling slightly (NSIDC 2020, unpaginated).

Ice Sheets, Glaciers, and Ice Shelves

The Antarctic Ice Sheet extends almost 14 million km^2 (5.4 million miles^2), roughly the area of the contiguous United States and Mexico combined, and is divided into the East and West Antarctic ice sheets and the Antarctic Peninsula (NSIDC 2020, unpaginated; see Figure 2.6).

Climate change has led to widespread shrinking of the cryosphere over the last decades, with mass loss from ice sheets and glaciers (IPCC 2019a, p. 6). Antarctic ice sheets are projected to lose mass at an increasing rate throughout the 21st century and beyond (IPCC 2019a, p. 17; NSIDC 2020; Meredith et al. 2019, p. 212). Although there is low confidence in these changes given the sparse in situ records and large inter-annual to inter-decadal variability (Meredith 2019, p. 212). Rapid ice loss from Antarctica ice sheets from 2012 to 2016 (–199 ± 26 gigatons per year (Gt yr–1)) was extremely likely greater than that from 2002 to 2011 (–82 ± 27 Gt yr–1) and likely greater than from 1992 to 2001 (–51 ± 73 Gt yr–1). Overall ice loss on Antarctica is dominated by acceleration, retreat, and rapid thinning of major West Antarctic Ice Sheet outlet glaciers that is driven by melting of ice shelves by warm ocean waters (Meredith et al. 2019, p. 206; IPCC 2019a, p. 6).

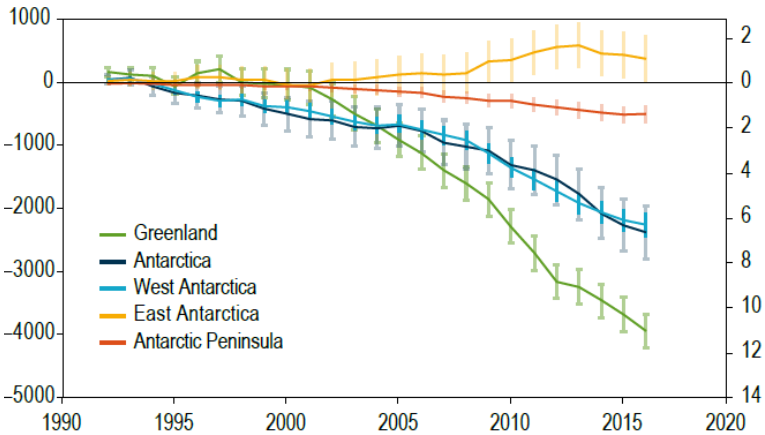

Figure 3.1. Cumulative ice sheet mass change 1992–2016. Y-axis is mass change (Gt); x-axis is year (Meredith 2019, p. 237).

Ice sheets in Antarctica flow outward from center and terminate at the ocean through glaciers and ice streams, forming ~~an~~ ice tongues and/or~~or~~ ~~an~~ ice shel~~f~~ves that fringe the continent. Antarctica has 15 major ice shelf areas; ice shelves surround approximately 75 percent of the continent's coastline. A critical feature of a glacier-ice shelf system is the "grounding line," - the point where the flowing ice begins to float. The location of the edge is very sensitive to both ocean condition and the amount of ice fracturing (crevasses or rifts). Ice shelves gain mass from ice flowing into them from glaciers on land, snow accumulation, and freezing of seawater underneath. Ice shelves lose mass by calving icebergs or melting from below, and wind drift on the surface. Calving of huge, tabular icebergs is unique to Antarctica, and the process can take a decade or longer (NSIDC 2020, unpaginated).

Catastrophic Events

On a stable ice shelf, iceberg calving is a near-cyclical, repetitive process producing large icebergs every few decades. Therefore, this event is not a good indicator of warming or climate change (NSIDC 2020, unpaginated). Furthermore, changes in Antarctic ice sheets have complex causes with low confidence attributing causes (Bindoff et al. 2014, p. 909). However, warmer temperatures can destabilize this system by increasing glacier flow speed, and more dramatically by disintegrating the ice shelf. Rapid ice shelf collapse is attributed to warmer air and water temperatures, as well as increased melt on the ice surface (NSIDC 2020, unpaginated). When certain thresholds are passed, catastrophic ice shelf disintegration through iceberg calving is initiated. Before collapse, ice shelves first undergo a period of long-term thinning and basal melting, making them vulnerable. Meltwater ponding on the surface and tidal flexure and plate bending then all contribute to rapid calving events and ice shelf disintegration (NSIDC 2020, unpaginated; Antarctic Glaciers 2020, unpaginated).

Rapid collapse of ice shelves or calving of icebergs could affect the emperor penguin, which mostly breed on sea (fast) ice at continental margins, and two case studies are presented to illustrate these effects. Generally, catastrophic ice shelf collapse or iceberg calving could cause mortality of chicks and adults, destroy a breeding colony, and prevent adult penguins from reaching their feeding ground. The effect would depend on the time of year (season) and the breeding colony's proximity to a collapsing ice shelf or calving iceberg (Fretwell and Trathan 2019, pp. 3–6; Kooyman et al. 2007, pp. 36–37).

It is unknown if emperor penguins would be able to adapt to a different breeding location such as ice shelves or on land. The adaptive capacity of emperor penguins is unknown, but the species has so far shown little evidence of adaptive capacity (Trathan et al. 2020, p. 7). Emperor penguin temporarily or permanently breeds on ice shelves at very few locations. The species has been known to relocate to another breeding colony when sea ice is no longer suitable (i.e., Halley Bay), or return to the same colony with lower abundance subsequent to a catastrophic event near that particular colony (i.e., Cape Crozier; Fretwell and Trathan 2019, entire; Kooyman et al. 2007, entire).

Sea ice provides a layer of protection between an ice shelf and the surrounding ocean, muting the power of large waves and storms (Massom et al. 2018, pp. 384–388). As sea ice decreases, more waves contact ice shelves. The largest waves can buckle and bend an ice shelf, increase instability and contribute to a collapse (NSIDC 2020, unpaginated; Massom et al. 2018, p. 383). The disintegration events of Larsen B, Larsen A, and Wilkins occurred temporally with sea ice loss that resulted in extensive and sustained periods of exposure of the ice shelves to open-ocean conditions (Massom et al. 2018, p. 385). Extreme waves are projected to increase in the Southern Ocean under RCPs 4.5 and 8.5 (Collins et al. 2019, p. 605; Meucci et al. 2020, p. 3). A review of 91 published global and regional scale wind-wave climate projection studies found a consensus on a projected increase in significant wave height over the Southern Ocean (Collins et al. 2019, pp. 604–605). Therefore, the emperor penguin at breeding colonies are likely to experience more catastrophic events such as iceberg calving, ice shelf disintegration, and/or storm events because these events are likely to increase in the future with increasing emissions (warming).

<u>Case Study – Cape Crozier and Beaufort Island/Ross Ice Shelf (Colonies 43 & 44 in Figure 2.10)</u>
In March 2000, a giant piece of the Ross Ice Shelf calved and formed the largest iceberg ever recorded from Antarctica. This iceberg (B15A) knocked another iceberg (C16) from the shelf; both then lodged near Ross Island. The icebergs broke off the promontory of the ice shelf that contained the colony of Cape Crozier. The position of the icebergs also may have hindered the arrival of many adults coming from a traditional molting area (Kooyman et al. 2007, p. 31).

At both colonies, a high amount of adult mortality occurred when the icebergs lodged near Ross Island. Adults were crushed, trapped in ravines, abandoned their chicks, and/or were prevented access to traditional feeding grounds at the Ross Sea polynya. The Cape Crozier colony produced 1,201 chicks in 2000. Following the iceberg calving and its movement toward the colony in January 2001, the next 4 years the number of chicks produced ranged from 0% in 2001 to 40% in 2004 of the chick production observed in 2000. In 2005, 273 adults were present but no breeding was observed. While these large icebergs have changed the sea ice distribution and access routes to foraging areas and generally reduced habitat quality, the colonies have persisted.

Based on the population trend from 1961–2004, these colonies must have dealt with similar events that occurred periodically (Kooyman et al. 2007, entire).

Case Study – Halley Bay Colony/Brunt Ice Shelf (Colonies 7 & 8 in Figure 2.10)
Halley Bay was one of the largest breeding colonies in Antarctica. The colony was located on the northern side of the Brunt Ice Shelf. The sheltered bays bordering the ice shelf usually retain fast ice until December and often the ice remains all summer. This ensures that emperor penguins are able to raise their chicks at the site as their young fledge between mid-December and early January (Fretwell and Trathan 2019, p. 1).

In October 2016, the sea ice broke out early, which resulted in total breeding failure at Halley Bay (Fretwell and Trathan 2019, p. 3). Emperor penguins have not successfully bred at this colony since. Sea ice that has reformed has not been strong enough and storm events occur in October and November that blow out the sea ice early (Fretwell and Trathan 2019, p. 3; British Antarctic Survey 2020, unpaginated). Breeding pairs have increased at nearby Dawson-Lambton colony because some, but not all, of the penguins from Halley Bay relocated (Fretwell and Trathan 2019, p. 3). It would be pointless to repopulate the Halley Bay location because the Brunt Ice Shelf is likely to calve, or break off in the future (Fretwell and Trathan 2019, p. 6; NOAA 2019, unpaginated).

Sea Ice

Total Antarctic sea ice cover exhibits no significant trend over 40 years of satellite observations (1979–2018; Ludescher et al. 2018, in Meredith et al. 2019, p. 214). To project the long-term viability of the emperor penguin, sea ice extent and/or concentration, and how it relates to the emperor penguin's long-term habitat availability, has been modeled under different climate change scenarios using an ensemble of climate models (Barbraud and Weimerskirch 2001, entire: Ainley et al. 2010, entire; Jenouvrier et al. 2012, 2014, 2017, 2019, entire).

Sea ice is sensitive to both the atmosphere and ocean; thus, it is an important indicator of polar climate change~~s~~ (Hobbs et al. 2016, p. 1543). Emperor penguins are~~is~~ a high latitude, sea ice obligate species and requires a stable breeding platform (sea ice) for 8–9 months for chicks to fledge, and require~~s~~ nearby polynyas or feeding grounds to supply food during this time. Therefore, emperor penguins depend upon stable fast ice for 8–9 months of the year and late formation in winter and/or early breakup of the ice in spring will reduce breeding success at any given colony. The effect of climate change is not projected to have a uniform effect on the entire continent of Antarctica (Ainley et al. 2010, p. 56; Jenouvrier et al. 2014, entire). ~~Meaning sea~~As a result, sea ice in some of the five sectors of Antarctica, and thus breeding colony locations, are projected to be more affected than other sectors. Therefore, changes to sea ice because of climate change would affect emperor penguins and their~~its~~ breeding habitat around the continent at different magnitudes and temporal scales.

Commented [HZ6]: This pretty much restates the sentence prior to it.

Sea ice extent and duration also affects breeding success (Yale Climate Connections 2020, unpaginated; Jenouvrier et al. 2014, p. 715; see *Habitat*, above). Extensive winter sea ice negatively affects hatching success by increasing the distance to feeding grounds from the colony, resulting in reduced food provisioning for chicks. However, extensive sea ice positively affects adult survival by increasing overall food availability because prey abundance is positively tied to sea ice extent. In population terms, the advantage of extensive (positive) sea ice that favors higher adult survival and further reproduction outmatches the disadvantage of also reducing fecundity by increasing distances to foraging areas (Barbraud and Weimerskirch 2001, p. 185). The population growth rate of long-lived species is mainly sensitive to changes in adult survival (Barbraud and Weimerskirch 2001, p. 184). Because emperor penguins depend~~s~~ on sea ice, climate change leading to a change in sea ice extent and duration will affect the emperor penguin's long-term viability at breeding colonies, and two case studies are presented below to illustrate these effects.

Commented [HZ7]: This whole section feels redundant. I think summarizing things a bit better and shortening it might help with clarity. I understand that there are many ways in which sea ice affects specific aspects of penguin breeding/viability but the way this information is presented here is somewhat muddled and the main points aren't coming across clearly to me

Case Study – Dion Islets (unnumbered green dot in Figure 2.10)

This colony was located on the western Antarctica peninsula, was one of the most northerly breeding locations, and was the fourth colony discovered. The colony was discovered in 1948 (Trathan et al. 2011, p. 1; Stonehouse 1952, p. 760). Sea ice conditions around the Dion Islands were recorded from 1961 until 1973, and although the quality of the annual record was variable, the date of the first and last fast ice formation was always recorded (Trathan et al. 2011, p. 2).

The winter sea-ice conditions at this colony were generally marginal for successful emperor penguin breeding, and this location was likely a high-risk site for incubating adults and chicks (Trathan et al. 2011, p. 5). The emperor penguin colony relied upon the availability of land in most winters, even when the population size was relatively stable up until the 1970s. This is one of very few colonies known to have bred on land as opposed to solely on fast ice (Trathan et al. 2011, pp. 2–5).

The population at this colony was always small (≈250 breeding pairs) and maintained a steady size until the early- to mid-1970s, after which the population continuously declined. By 1999, there were fewer than 20 pairs, and in 2009, no trace of the colony remained (Trathan et al. 2011, p. 2). The demise of the colony from 1970s onwards was extremely rapid (taking just over 30 years)~~,~~ compared to the average lifespan of an individual (approximately 15–20 years). The most likely cause of the decline and extirpation was a chronic reduction in sea ice habitat, including interactions with the food web, associated with local atmospheric warming (Trathan et al. 2011, p. 2). This was the first documented extirpation of a breeding colony.

Case Study –Pointe Géologie colony at Terre Adélie (Colony 35 in Figure 2.10)

The emperor penguin colony located near Dumont d'Urville Station in Terre Adélie (Pointe Géologie) is monitored continuously and generates the longest data set available on an Antarctic marine predator (Barbraud and Weimerskirch 2001, p. 183). From 1962 onward, breeding adults, number of eggs, frozen chicks, and surviving chicks at the end of the breeding season have been counted, ~~which~~ providing an~~es the~~ estimation of breeding success (Barbraud and Weimerskirch 2001, p. 183; Jenouvrier et al. 2012, p. 2756).

The population of emperor penguins at this colony was stable until the mid-1970s and abruptly declined by 50 percent in the late 1970s, a time with an abnormally warm period and the lowest sea ice extent recorded at this location (Barbraud and Weimerskirch 2001, p. 183; Jenouvrier et al. 2012, p. 2766). The population has stabilized since the decline and exists as a smaller population compared to pre-decline population size (Barbraud and Weimerskirch 2001, p. 183).

See Figure 3.2 for breeding pairs estimate at this colony from 1955 to 2015 (Trathan et al. 2020b, p. 21). Breeding success varied extensively and its variability has increased progressively since the 1970s due to a combination of factors (Barbraud and Weimerskirch 2001, p. 185; Trathan et al. 2020, p. 21). Complete or extensive breeding failure in some years occurred because of early break out of sea ice, or from prolonged blizzards during the early chick-rearing period (Barbraud and Weimerskirch 2001, p. 185). Breeding success over six decades (1950s–2010) has ranged from 3–86% and adult survival ranged from 60–98% (Barbraud and Weimerskirch 2001, in Jenouvrier et al. 2012b, p. 31).

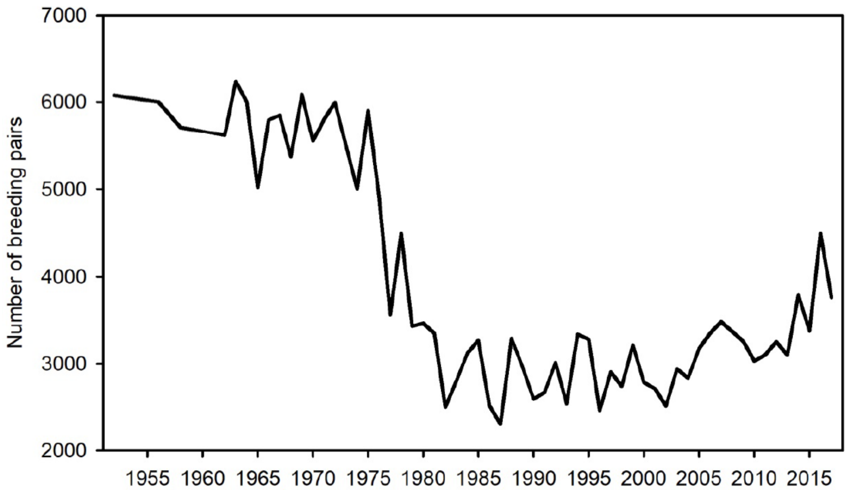

Figure 3.2. Population of emperor penguin breeding pairs at Pointe Géologie (Trathan et al. 2020).

A population viability analysis projecting the population ~~for~~ of emperor penguins at the Pointe Géologie colony was generated by linking stage-structured demographic models to sea ice forecasts based on an ensemble of climate models (from Jenouvrier et al. 2012, entire).

Five climate models were used that contained outputs of sea ice that agreed well with historical observations of sea ice and were forced with a middle range emissions scenario (SRES A1B[6]). All five models agree that the smoothed mean sea ice concentration will decline by 2100, but the rate of decline varies between climate models and seasons.

The median of the 200,000 population projections, starting with the 2010 population of 3,000 breeding pairs, varied considerably with some increasing or decreasing rapidly, and some

[6] The Special Report on Emissions Scenarios (SRES) were succeeded by Representative Concentration Pathways (RCPs) for projecting future climate change. These two families of scenarios are commonly used for future climate projections: the 2000 SRES and the 2010 RCP; Global Change 2020, unpaginated). SRESs are named by family with each family based around a set of consistent assumptions. RCPs are numbered according to the change in radiative forcing by 2100. SRES A1B is consistent with RCP 6.0 (Melillo et al. 2014, p. 755)

Commented [HZ8]: Before stating this here, I think it would help to state somewhere in the above paragraph, or at the end of the one just before it, that 200,000 projections were created using climate model output (presumably) from the 5 climate models remaining stable ~~then~~ but followed by a decline. However, for each model there existed a year beyond which the median projected population declines. This tipping year may be late (e.g. 2089; *ukmo-hadcm3*) or early (e.g. 2038; *cccma cgcm3-1-t63*) and varies among trajectories, depending on the forecasted sea ice, the responses of the vital rates, and the sex-specific adult survival on the demography. The decline in the median of the 200,000 population trajectories accelerates after 2040 because more of the population trajectories are likely to have reached their tipping year as time goes on.

By the end of the century, the medians of all models (except *ukmo-hadcm3*) projected that the number of breeding pairs will decline compared to the minimum number over the past six decades. Overall, by the end of the century, the median breeding pairs is projected to decline from 3,000 to 575 (81% decrease), and there is a 43% chance for the population to decline by at least 90%. The range of uncertainty might change the details but not the overall biological conclusion that the population declines (Jenouvrier et al. 2012, entire).

Table 5. Probabilities from the five models that the population at Terre Adélie will decline by more than 90% from 2010–2040, 2060, 2080, and 2100.

Models	**2040**	**2060**	**2080**	**2100**
cccma-cgcm3-1	0.0168	0.2366	0.7625	0.9903
cccma-cgcm3-1-t63	0	0.0205	0.6783	0.9997
ukmo-hadcm3	0	0	0	0.0001
ukmo-hadgem1	0	0.0001	0.0088	0.1276
mp1-echam5	0	0	0	0.0181
Entire Set	**0**	**0.0514**	**0.2899**	**0.4272**

Prey Abundance and Sea Ice

Emperor penguins have a varied menu that varies with time of year and location and may vary at the same site between years (see *Food and Feeding Behavior*, above). They feed mostly on fish, krill, and squid, and currently, as discussed below, prey availability is not a limiting factor for ~~emperor penguin~~them. Emperor penguins hunt opportunistically, although some prey are more important, such as the Antarctic silverfish that is always a main component of the diet and occurs in all coastal regions of the continental Antarctic. Polynyas are prime foraging habitat because they provide the closest open water to the colony and have high productivity (food). Almost all colonies occur near polynyas.

Antarctic Silverfish

The Antarctic silverfish has a circum-Antarctic distribution (La Mesa and Eastman 2012, p. 245) and is the dominant pelagic fish in all regions of the coastal regions of the continental Antarctic (Vacchi et al. 2012, p. 11; Cherel and Kooyman 1998, p. 335; Trathan et al. 2020, p. 3; Australian Antarctic Division 2020, unpaginated; Mintenbeck and Torres 2017, p. 253). The silverfish's pelagic lifestyle makes it a key diet component of coastal Antarctic apex predators and is a significant part of the emperor penguin's diet (Mintenbeck and Torres 2017, p. 255). The seasonality of ice, sunlight, and pelagic production strongly influence the silverfish's life cycle. Adults migrate inshore for spawning during winter because the presence of coastal sea ice when spawning occurs is important, as eggs have been found under sea ice, which acts to prevent or reduce predation (La Mesa and Eastman 2012, p. 257). Sea ice is present at the time of spawning throughout the species' range (Mintenbeck and Torres 2017, p. 259).

The current temperature over the known range of Antarctic silverfish is not affecting the growth or development of the species. Most Antarctic fish have narrow thermal tolerances as an adaptation to colder waters. The vast majority of its range has year-round temperatures of -2 °C and significant ice cover (Zwally 2002, in Mittenbeck and Torres 2017, p. 255). On the western Antarctic Peninsula, the species occurs within a temperature range of -2 to 2 °C (Lancraft et al. 2004; Donnelly and Torres 2008, in Mittenbeck and Torres 2017, p. 266). There are no experimental data describing upper temperature limits (Mittenbeck and Torres 2017, p. 265). Although there has been a documented decline of the species in the western Antarctic Peninsula related to regional warming and effects on seasonal sea ice (Mittenbeck and Torres 2017, p. 275).

Spatiotemporal changes in phytoplankton and zooplankton community structure because of changes in sea ice, from krill-dominated zooplankton community to a salp (*Salpa thompsoni*)-dominated community, would have substantial effects to the food web (Atkinson et al. 2004; Atkinson et al. 2008; Suprenand and Ainsworth 2017). Fishes, particularly small pelagic zooplankton consumers, are known to be highly sensitive to indirect effects of alterations in prey abundance, prey composition, and prey size (Mintenbeck and Torres 2017, p. 267). The Antarctic silverfish is a key species in the high Antarctic food web, as prey for higher predators, and as predators of krill and other food sources. The energy density and nutritive value of gelatinous species (i.e., salps) compared to crustaceans such as krill and copepods is extremely low (Mittenbeck and Torres 2017, p. 268). Therefore, a mismatch between larval silverfish and prey availability due to climate change would affect growth and recruitment of silverfish because larvae strongly depend on prey abundance, type of prey, and seasonal timing (Beaugrand et al. 2003, p. 661). It is very likely that changes in sea-ice dynamics will involve alterations in all three of these parameters (Mittenbeck and Torres 2017, p. 262). Generally, the species would be sensitive to any climatic or oceanic change that reduced the extent of sea ice or the timing and/or formation of coastal polynyas (La Mesa and Eastman 2012, p. 243).

Most effects of increasing temperatures associated with climate change will be indirect, as temperatures will not reach physiologically life-threatening levels in the short term (Mintenbeck and Torres 2017, p. 253). The cumulative effects of several stressors, such as competition, predation, changing prey spectrum, reduced sea ice, episodic recruitment, and the physiological effects of warm temperature is likely to work in tandem ~~together~~ to put a high level of pressure on Antarctic silverfish (Mintenbeck and Torres 2017, p. 269).

Antarctic Krill

Krill habitat lies between the Polar Front to the north and the ice-covered Antarctic shelves to the south, but krill do not occupy all of this range (Atkinson et al. 2004, p. 101; Atkinson 2009, p. 734). Krill are concentrated in the southwest Atlantic and extend around Antarctica, close to the continent. Seventy percent of the total stock of krill exists from 0° to 90 °W (Atkinson 2008, p. 8). Figure 3.3 below shows the distribution of krill around Antarctica (Ancel et al. 2017, p. 172; Atkinson et al. 2008, p. 4).

Recruitment success and thus population size of krill are linked to winter sea ice and food availability (Atkinson et al. 2004, p. 102; Atkinson et al. 2008, p. 13; Seigel and Loeb 1995, pp. 52–54). In years following winters with expansive sea ice extent and duration, krill reproductive success increases (Loeb et al. 1997, p. 898; Siegel and Loeb 1995, p. 54). Years with low sea ice correlates to poor recruitment or low abundance of krill the following summer in the same area; however, only a few years per decade are needed to maintain the local krill population (Atkinson et al. 2004, p. 102). Population size of krill seems largely driven by recruitment success rather than predation pressure on post-larval krill (Atkinson et al. 2008, pp. 15–19). Recruitment, driven by winter sea ice and survival of larval krill, is probably the population parameter most susceptible to climate change (Flores et al. 2012, p. 1).

Sea ice acts as a shelter, feeding ground, and a transport platform for krill larvae (Flores et al. 2012 p. 4). Adult krill are able to survive without food during the winter, whereas larvae cannot tolerate long starvation periods, making them dependent on biota associated within and below winter sea ice (Meyer et al. 2009, p. 1595). As sea ice melts, it releases algae and nutrients into the water, stimulating phytoplankton blooms in the marginal ice zone. These sea ice-induced blooms play a key role in the summer because krill need summer phytoplankton blooms to feed (Hempel 1985, in Flores et al. 2012, p. 4).

Sea ice, oceanography, and nutrients promote primary production near shelves and ice edges, and krill occupy this full range of habitats. Within the distributional range of krill, their mean density correlates positively with the concentration of chlorophyll a (Atkinson et al. 2004, p. 102; Atkinson et al. 2008, p. 13).

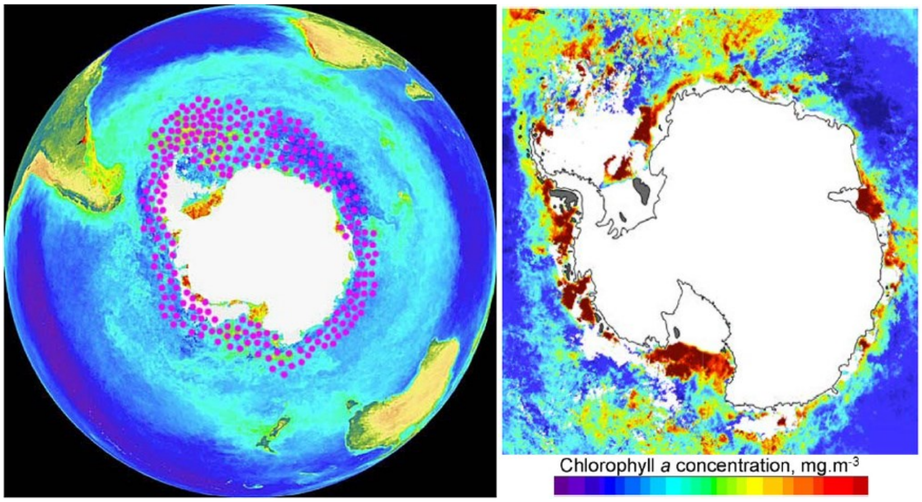

Figure 3.3. (a) Pink dots represent krill distribution around the Antarctic Continent.(b) Concentration of chlorophyll a (Average summers 2002–2012) (Ancel et al. 2017).

As krill densities have decreased because of changes in sea ice, salps have increased in the southern part of their range (Atkinson et al. 2004, p. 100). However, the degree to which salps become prominent in the future remains uncertain because the drivers of their abundance have not been explained. Salps and krill are adapted to be successful in different environments, namely open ocean and coastal regions, respectively (Constable et al. 2014, p. 3013). Salps show no relationship to sea ice extent or duration, whereas extensive winter sea ice promotes survival of larval krill (Loeb et al. 1997, p. 898; Atkinson 2004, p. 102).

The western Antarctic Peninsula is one of the fastest warming places on the planet and the duration of winter sea ice in this area is shortening (Parkinson 2019, p. 14419; Atkinson et al. 2004, p. 102). Krill density in the southwest Atlantic has decreased significantly since the 1970s, accompanied by an increase in temperature and a decrease in sea ice (Atkinson et al. 2004, p. 102; Atkinson et al. 2008, p. 8). The reduction in sea ice duration and distribution will likely have a negative effect on reproductive success and survival of krill (Flores et al. 2012, p. 4). Antarctic krill is a keystone species throughout its range because it provides a vital link to higher levels of the food web as many marine mammals and birds feed on krill (Oceana 2020, unpaginated). A decrease in krill coinciding with a decrease in sea ice could have profound implications for the Southern Ocean food web (Atkinson 2004, p. 103).

Modeling potential changes to krill recruitment and distribution under climate change projects a loss in biomass of krill under both RCPs 2.6 and 8.5 (Klein et al. 2018, p. 7; Suprenand and Ainsworth 2017, p. 47; Flores et al. 2012, p. 4). The optimal conditions for krill are expected to move southward to higher latitudes because of a change in sea ice extent and duration. The areas with the largest decrease are in the areas with the most rapid warming (Atkinson et al. 2019, p. 144; Meredith et al. 2019, p. 231). For example, the krill biomass is declining and the distribution is changing in the southwest Atlantic Ocean because of productivity changes tied to warmer weather and a decline in sea ice (Atkinson et al. 2004, entire; Atkinson et al. 2019, entire).

<u>Squid</u>

Squid are an important part of the diets of Southern Ocean higher predators. There are at least 18 species of squid in the Southern Ocean and distribution of squid fauna is determined by latitude. All species of squid have a circumpolar distribution, although there may be gaps or a lack of abundance in areas (Rodhouse 2013, p. 130; Collins and Rodhouse 2006, p. 249). It is unlikely that temperature increases per se would affect squid in the Southern Ocean, other than perhaps reducing the northern limit of their range. Squid fauna extend as far north as the Antarctic Polar Front and can tolerate a wide range of temperatures (Rodhouse 2013, p. 135). Additionally, there is no evidence that Antarctic squid have any direct dependence on sea ice so there is no obvious reason why changes in sea ice would have any direct effect on squid populations (Rodhouse 2013, p. 135).

<u>Ocean Acidification Effects on Emperor Penguin Prey</u>

Seawater is not acidic, nor is it ever likely to be, but because of the buildup of carbon dioxide (CO_2) in our atmosphere, more CO_2 is absorbed by the oceans and makes them more acidic than they used to be (Winner 2010, unpaginated). Approximately one-quarter of the carbon dioxide released by human activities dissolves in surface water, which causes a decrease in pH and carbonate ion (CO_3^{2-}) (Meredith et al. 2019, p. 218). These changes, together known as 'ocean acidification' have direct consequences for the marine calcium carbonate ($CaCO_3$) cycle and those species that interact, exploit, and secrete the mineral (McNeil 2010, p. 1). It can affect organisms that form shells and skeletons using calcium carbonate, aragonite and calcite as dominant mineral forms by increasing energetic costs of calcification (Meredith et al. 2019, p. 218). Ocean acidification is a concern not only for calcifying organisms but also for the development of crustaceans such as Antarctic krill, as well as squid (Constable et al. 2014, p. 3004; Kawaguchi et al. 2013, pp. 844–845; Kaplan et al. 2013, entire).

Ocean acidification is a predictable consequence of rising atmospheric carbon dioxide (CO_2~~^{2}~~) and does not suffer from uncertainties associated with climate change forecasts (Doney 2009, p. 170). Absorption of anthropogenic CO_2~~^{2}~~, reduced pH, and lower calcium carbonate ($CaCO_3$) saturation in surface waters are well verified from models, hydrographic surveys, and time series data (examples in Doney 2009, p. 170). Increased uptake of CO_2~~CO2~~ in oceans has lowered the pH of seawater by 0.1 unit since the industrial revolution and is projected to decrease up to 0.5 pH units at higher CO_2~~CO^2~~ concentration (800 ppm), which is equivalent to a tripling of hydrogen ion concentration (Orr et al. 2005, p. 681; Doney 2009, p. 170; Rodhouse 2013, p. 135). This low pH level would be the lowest in millennia and with a higher rate of change than has ever occurred in the same time period (Rodhouse et al. 2013, p. 135). High latitude ocean (i.e., Southern Ocean) would be first to become under-saturated with respect to calcium carbonate (Cao 2008, p. 3; The Royal Society 2005, p. 29).

Summary

The life histories of primary prey species of the emperor penguin are tied to photoperiod, sea ice extent and duration, and phytoplankton production (Atkinson 2004, p. 102; Mintenbeck and Torres 2017, p. 262). Currently, prey availability is not a limiting factor for emperor penguins because of extensive sea ice around the continent, food resources are circumpolar, and most breeding colonies are located near polynyas. The effect of prey abundance, relative to changes in sea ice and ocean acidification caused by climate change, on emperor penguins and other marine life in the Southern Ocean could be substantial. However, the effect of climate change on Southern Ocean pelagic primary production is difficult to determine given that the time series data is insufficient (less than 30 years) to attribute a climate change signature and may be due to a combination of climate change and natural variability (Meredith et al. 2019, p. 230; Ainley et al. 2010, p. 63). The food web is very complex and may involve decreases in certain prey (e.g., Antarctic krill) and increases in others (e.g., crystal krill [*Euphausia crystallorophias*]; La Mesa et al. 2004, p. 330; Ainley et al. 2010, p. 63). Additionally, the Southern Ocean food web is undergoing adjustment as some species recover (i.e., humpback whales) and others decrease due to industrial fishing, sealing, and whaling (Ainley et al. 2010, p. 63; Nicol et al. 2008, p. 372; IPCC 2014b, p. 1577). Therefore, it is challenging to differentiate effects of climate change from other factors that may affect the emperor penguin's prey base. The best available information projects that sea ice condition will decrease at a higher rate under higher emission scenarios than low or moderate emission scenarios. Because the emperor penguin's primary prey species are positively tied to local sea ice conditions, subsequent distresses to the food web because of changes in sea ice increases the risk to emperor penguin over the long term.

Other Stressors

Humans have the possibility to affect emperor penguins through activities of tourism, ecological contamination, and commercial fishery operations. These stressors have minor indirect effects on emperor penguins and are located or would affect a very small portion of the population.

Tourism

Antarctica emerged as a tourist destination in the late 1950s and humans have been visiting for more than 60 years (Enzenbacher 1992, p. 18; IAATO 2019, p. 1). Ships and aircraft bring tourists to Antarctica; nearly all tourists travel by sea rather than air (Enzenbacher 1992, p. 18; IAATO 2019, p. 4). The annual number of tourist visits reached a peak in 2007–2008 season with 46,265 visitors, a sharp decline followed due to the global economic crisis, and then reached new peak visitors with 56,168 in 2018–2019 (IAATO 2019, unpaginated). The tourism season in Antarctica is roughly from November through March, which partially overlaps the breeding season when emperor penguins are rearing their chicks and actively foraging for food. The rest of the tourism season is during the austral summer when emperor penguins are not breeding.

In 1991, tour operators founded the International Association of Antarctica Tour Operators (IAATO). The large majority of tour operators are members of IAATO and work within the Antarctic Treaty System to ensure their activities have no more than a minor effect to the environment (IAATO 2019, unpaginated). Because the IAATO includes the large majority of tour operators to Antarctica, Figure 3.4 is a good estimate of the level of tourism. Antarctica will have increased tourism pressure as trips become easier to arrange, as more seabird colonies become accessible, and as interest grows in this polar habitat (Burger and Gochfeld 2007, p. 1310). However, future levels of Antarctic tourism is difficult to predict and the total number of tourists is difficult to determine with certainty (Enzenbacher 1992, pp. 17, 21). The most frequently visited area of Antarctica is the peninsula and many areas of Antarctica are not accessible.

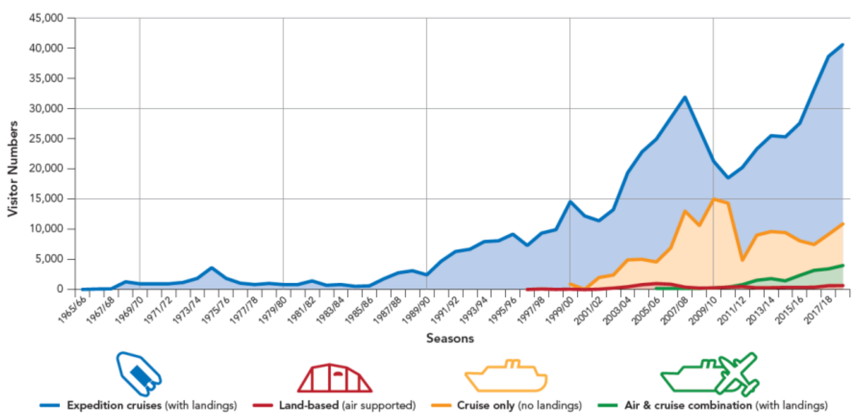

Figure 3.4. Number of visits to Antarctica, from 1965/66 to 2018/19 (IAATO 2019).

Several studies report a range of behavioral responses of penguins to tourists (Burger and Gochfeld 2007, p. 1303; Harris 2005, p. 317). One study on emperor penguins examined the influence of tourists on emperor penguins traveling across the ice from breeding colony to feeding ground. These emperor penguins at the Snow Hill colony had virtually no prior experience with humans (Burger and Gochfeld 2007, p. 1304).

There were two main effects in penguin behavior: penguins required more time to cover the same distance, and they used more energy (Burger and Gochfeld 2007, p. 1310). Noticing people usually meant penguins stopped tobogganing, stood up and looked at people, and often vocally notified companions behind them. Emperor penguins resort to standing up when frightened (Murphy 1936, in Burger and Gochfeld 2007, p. 1307). Once the penguins passed humans, they usually started tobogganing again. The time for emperor penguins to travel from the Snow Hill colony to the sea was estimated to take at least 6 hours. Walking has considerable energy costs for penguins compared to tobogganing. Therefore, human presence delaying penguins reaching the sea or breeding colony site has additional energy costs (Burger and Gochfeld 2007, p. 1307). Most birds did not appear overtly alarmed, although some altered their path quickly and retreated. Overall, the number and duration of pauses increased significantly with increases in the number of tourists in their path and their behavior in proximity to humans is directly related to the number of humans present (Burger and Gochfeld 2007, pp. 1306–1307).

Aircraft operations in Antarctica occur in the summer months of October–March for operation of research stations and tourism (Harris 2005, p. 310). The general response of chicks to helicopters was to: (1) become more vigilant, (2) flap their flippers while stationary, (3) walk less than 10 m, often while flipper flapping, and (4) run, usually less than 10 m. The tendency was for chicks to shuffle together rather than to scatter. Overall, the behavioral responses of chicks were relatively transitory, lasting only as long as the helicopter was in range of the birds (Giese and Riddle 1999, pp. 369–370). Energy expenditure induced by repeated helicopter disturbance could have implications for chick fledging and subsequent survival. However, guidelines from the Antarctic Treaty requires certain recommendations if aircraft operate close to concentrations of birds. Measures include maintaining minimum overflight distances, minimum distance landing near a colony, avoiding protected areas (see **Conservation and Management Actions**, below), and avoiding effects to breeding and molting birds (Secretariat of the Antarctic Treaty 2020, unpaginated). Therefore, aircraft operations for research station operations and tourism is not likely to have more than a minor and temporary indirect effect to the emperor penguin population.

Because tourism is mostly in the Antarctic Peninsula, most of the other colonies would not be subject to tourism. Tourism operators work with the Antarctic Treaty System to ensure their activities have no more than a minor effect to the environment. Therefore, even if tourists are able to access more of Antarctica if sea ice decreases around the continent in the future, the indirect and temporary effect of human tourists is not a driving factor of the emperor penguin's viability.

Contaminants

The Southern Ocean forms a boundary between Antarctica and other bodies of water (Corsolini et al. 2003, p. 95). Despite the natural oceanic barriers to protect Antarctica from lower latitude water, persistent contaminants (i.e., metals, petroleum products, persistent organic pollutants) are transported to the Antarctic environment from countries in the Southern Hemisphere (Bargagli 2008, entire). Atmospheric transport provides the means by which contaminants reach Antarctica (Corsolini et al. 2003, p. 95). The pollutants accumulate in ice and snow and the summer thaw releases the pollutants, which can then enter trophic webs (Corsolini et al. 2003, p. 95; Norwegian Polar Institute 2020, unpaginated).

The combustion of fuel for transportation and energy production, waste, sewage, shipwrecks, and accidental spills are among the sources of contaminants in the Antarctic environment (Bargagli 2008, p. 213). Fuel-oil spills are one of the most widespread sources of localized pollution near scientific stations (Bargagli 2008, p. 217). Local pollution around scientific stations has been a concern since the 1970s, and through the 1980s, because waste at most Antarctic stations was dumped in landfill sites close to the station, into the sea, or burnt in the open air (Bargagli 2008, p. 213).

The Protocol on Environmental Protection to the Antarctic Treaty (Protocol), signed in 1991 and entered into force in 1998, designated Antarctica as a natural reserve and described the basic principles of human activities in Antarctica. Particular to waste management and marine pollution, the Protocol requires that the amount of waste must minimize impacts on the environment and contains rules for discharge of any noxious liquid or sewage within the Antarctic Treaty area. The Protocol provided strict guidelines for environmental management and protection, and established the obligation to clean-up abandoned work sites (Secretariat of the Antarctic Treaty 2020, unpaginated; see **Conservation and Management Actions**, below).

Contaminants have been found in krill and silverfish in the Ross Sea (Corsolini et al. 2003, entire). These are two key prey species of the emperor penguin. There is no information for pollution effects on emperor penguin. However, concentrations of persistent organic pollutants were found in stomach contents of Adélie penguin, which fed primarily on krill and silverfish (Corsolini et al. 2003, p. 98). Some of these chemicals may be transferred through the tropic web through bioaccumulation and biomagnification and be harmful in the long term (Corsolini et al. 2003, p. 95). Although concentrations of most elements are low in Antarctica compared to data reported for most species from other marine environments of lower latitudes (Bargagli 2008, p. 216; Corsolini et al. 2003, p. 102; Norwegian Polar Institute 2020, unpaginated; Australian Antarctic Program 2020, unpaginated). Because strict protocols are in place to prevent and minimize effects to the Antarctic ecosystem from pollution and waste, and the concentrations of most elements are lower in Antarctica than other marine environments, the indirect effect of exposure to contaminants through the food web would be a minor effect to emperor penguin.

Commercial Krill Fishery

Antarctic krill sustain the largest fishery in the Southern Ocean (ATME 2010, p. 6). The commercial fishery began in 1961–1962 by the USSR, and by the mid-1970s a multi-vessel, multi-nation fishery was active (CCAMLR 2020, p. 3). Nineteen nations have historically reported catches of krill; from 2010–2019, eight nations reported catches of krill (CCAMLR 2020, p. 4).

Historical fishing grounds and seasons are changing as new areas become more accessible, the season is longer because of later formation of sea ice, and new participants engage in the fishery (Santa Cruz et al. 2018, pp. 162–163; Reiss et al. 2017, p. 12). As the krill fishery has developed, the location of fishing has moved from the Indian Ocean to the Atlantic Ocean sector and has been focused almost entirely in this sector since the early 1990s (Figure 18). From 1980–2005, catches were highly concentrated around Elephant Island and north of Livingston and King George Islands followed by a southward expansion towards the Bransfield Strait (Santa Cruz et al. 2018, p. 163). In the past 10 years, the spatial distribution of the fishery has been focused in the region of the Bransfield Strait off the Antarctic Peninsula (Subarea 48.1), to the northwest of Coronation Island (Subarea 48.2,) and to the north of South Georgia (Subarea 48.3; CCAMLR 2020, p. 4). There is allowable fishing for krill in Divisions 58.4.1 and 58.4.2, but there was no commercial krill fishing in these two divisions between 1991 and 2016 and only small level of catches since 2017 (CCAMLR 2020a, p. 4).

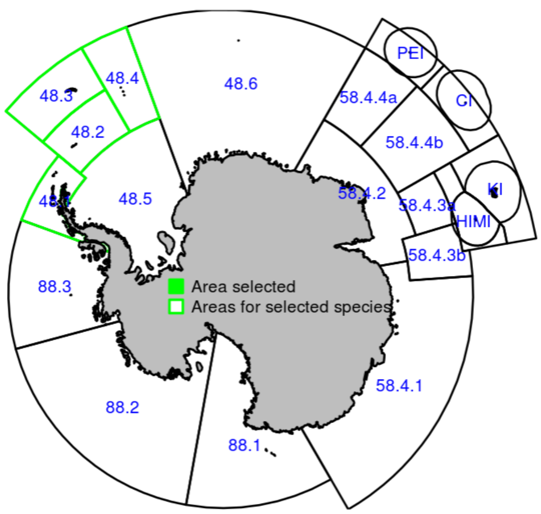

Figure 3.5. The Convention Area and the subareas where the krill fishery is currently concentrated (green subareas of 48.1–48.4) (CCAMLR 2020)

The fishing fleet could be considered an additional predator in the extensive list of krill-dependent predators in the Antarctic ecosystem (Santa Cruz et al. 2018, p. 165). Although the krill fishery is likely only a minor predation loss that historically operates below the allowable catch limits (Atkinson 2009, p. 738).

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) was established in 1980 because of the expanding krill fishery and potential impacts on the Southern Ocean ecosystem (CCAMLR 2020c, unpaginated). The Ecosystem Monitoring Program was established in 1985 to monitor the effects of fishing on both the harvested species and dependent species, i.e., predators of the harvested species (ATME 2010, p. 7). They set the catch limits for krill and implement conservation measures within the convention area to manage the krill-based ecosystem and provide a basis to regulate harvesting of Antarctic marine living resources in accordance with the 'ecosystem approach' (CCAMLR 2020a, p. 17). The CCAMLR set a catch limit of 3.47 million tons in any fishing season in Area 48. Catch limits are based on the best estimate of krill biomass, although this estimate may not account for factors such as climate change (CCAMLR 2020b, p. 2; ATME 2010, p. 6). To avoid localized impacts, a much lower 'trigger level' of 620,000 tons per season in subareas 48.1–48.4 combined was set to ensure continued input from the Commission (CCAMLR 2020a, p. 6). At no point in history of the krill fishery has a catch as high as 620,000 tones been taken in one year (CCAMLR 2020b, p. 2).

Emperor penguin adults and juveniles may forage in the areas of the krill fishery because of nearby colonies on the Antarctic Peninsula and in the Weddell Sea and juveniles typically disperse north after fledging to warmer open waters before returning south to the sea ice zone. The fishery is likely to expand further south as climate change affects the spatial distribution of sea ice and krill and there is interest in increasing the catch limits. A continued reduction in one of the emperor penguin's main prey species may affect emperor penguin into the future. However, krill fisheries are a minor effect because the fishery is at the northern tip of the Antarctic Peninsula, emperor penguins are opportunistic hunters, prey are readily available in areas outside of the fishery, and the fishery is regulated.

Conservation and Management Actions

The Antarctic Treaty System, first signed in 1959 by 12 nations, is the collective term for the Antarctic Treaty and related agreements (Secretariat of the Antarctic Treaty 2020, unpaginated). The treaty system regulates international relations with respect to Antarctica. Fifty-four countries have acceded to the Treaty and 29 of them participate in decision making as Consultative Parties (Meredith et al. 2019, p. 270). Protection of the Antarctic environment has been a central theme in the cooperation among Antarctic Treaty Parties (Secretariat of the Antarctic Treaty 2020, unpaginated).

The Antarctic Conservation Act of 1978 (ACA) conserves and protects the native fauna and flora of Antarctica and the ecosystem upon they depend (16 USC 2401). The ACA applies to the area south of 60° S latitude (16 USC 2402).

The CCAMLR was established by international convention in 1982 with the objective of conserving Antarctic marine life (CCAMLR 2020d, unpaginated). This was in response to increasing commercial interest in Antarctic krill resources, a keystone component of the Antarctic ecosystem and a history of over-exploitation of several other marine resources in the Southern Ocean (CCAMLR 2020d, unpaginated). See *Tourism*, above. Twenty-seven countries are party to the convention on the CCAMLR (Meredith et al. 2019, p. 270).

The Protocol on Environmental Protection to the Antarctic Treaty (Protocol) was signed in 1991 and entered into force in 1998. It designates Antarctica as a "natural reserve, devoted to peace and science" (Article 2). Article 3 of the protocol sets forth basic principles applicable to human activities (i.e., scientific research) in Antarctica. Article 6 promotes cooperation between Parties. Article 7 prohibits all activities relating to mineral resources, except for scientific research. Until

2048, the protocol can be modified only by unanimous agreement of all Consultative Parties to the Antarctic Treaty. In addition, the prohibition on mineral resource activities cannot be removed unless a binding legal regime on Antarctic mineral resource activities is in force. Forty countries have ratified the Protocol (Secretariat of the Antarctic Treaty 2020, unpaginated). The Protocol has six Annexes (I–VI). Annex III-Waste Management and Disposal applies to scientific research programs, tourism, and all other activities in the treaty area (Secretariat of the Antarctic Treaty 2020, unpaginated). It requires waste produced or disposed of shall minimize impacts on the Antarctic environment and minimize interference with the natural values of Antarctica consistent with the Antarctic Treaty. Annex IV-Prevention of Marine Pollution prohibits discharge of oil, noxious liquid substances, and garbage in the treaty area (Secretariat of the Antarctic Treaty 2020, unpaginated). Annex V-Area Protection and Management enables the Antarctic Treaty Parties to designate Antarctic Specially Protected Areas (ASPAs) to protect environmental, scientific, aesthetic, or wilderness values, any combination of those values, or ongoing or planned scientific research. Parties can also designate Antarctic Specially Managed Areas (ASMA) to assist in cooperation of activities to minimize environmental impacts (Secretariat of the Antarctic Treaty 2020, unpaginated). ASPAs are more restrictive than ASMAs. The ASPAs can be on land or at sea (marine protected areas); although the designation of large marine protected areas has largely been left to the CCAMLR (Trathan et al. 2020, p. 7). Marine protected area boundaries may also include ice shelves, adjacent fast ice and pack ice; therefore, potentially affording more complete protection for emperor penguins at their breeding site and while feeding or molting at sea (Trathan et al. 2020, p. 7).

To date, eight ASPAs have been designated that include protection for emperor penguin at their breeding sites, although these offer limited protection while birds are at sea even though some include a small marine component. The Ross Sea Region MPA was designated by CCAMLR to include protection for emperor penguins, and encompasses breeding sites at Cape Roget, Coulman Island, Cape Washington, Franklin Island, Beaufort Island, Cape Crozier and Cape Colbeck. It also includes protection for important feeding areas, as well as molt areas in the eastern Ross Sea. Thus, to date, seven active breeding sites are protected by ASPAs and seven by the Ross Sea Region MPA (of which three are also protected by ASPAs) (Trathan et al. 2020, p. 8).

CHAPTER 4: CURRENT CONDITION

The current condition of emperor penguin is based on population abundance (i.e., number of breeding pairs) at each colony and rangewide, and the sea ice condition measured as yearly sea ice extent (10^6 km^2). Emperor penguin depends on sea ice to use as a breeding platform to complete its annual breeding cycle, and promote primary production to provide abundant prey populations. Therefore, the projections of sea ice condition and the emperor penguin population are directly related, and sea ice serves as a proxy measure of all important habitat factors for the species. The resiliency of emperor penguin at each colony is tied to the sea ice conditions at that particular colony. The sea ice condition is described within five sectors (Weddell Sea, Indian Ocean, Western Pacific Ocean, Ross Sea, and Bellingshausen-Amundsen Seas; Figure 2.6), which may roughly correspond to some known genetic variation among colonies (Figure 2.1), and the Southern Ocean as a whole.

Emperor Penguin Population

Historically, identifying the location and size of emperor penguin colonies usually involved population counts and mapping on the ground or aerial photographs. As satellite imagery has been used to discover and rediscover colonies, the number of extant colonies and the population abundance has increased.

As of 2020, 61 emperor penguin breeding colonies are extant (Figure 2.10 and Table 2; Fretwell and Trathan 2009; Fretwell et al. 2012, 2014; Wienecke 2011; Ancel et al. 2014; LaRue et al. 2015; Ancel et al. 2017). The colonies are distributed around the continent of Antarctica. Table 2 contains estimated population sizes for each known breeding colony and notes the four colonies that were not extant in 2019 and one extirpated colony. The 11 newly discovered and/or rediscovered colonies do not contain population estimates. However, these 11 colonies increases the number of colonies by almost 20 percent and the total population 5 to 10 percent (approximately 25,000–55,000; 10,000–22,000 breeding pairs). Overall, the total population is approximately 270,000–280,000 breeding pairs.

Sea Ice

Sea ice concentration and sea ice extent[7] are influenced by the interconnected atmosphere-ice-ocean system of the Southern Ocean, including strength of near-surface winds, air temperature, ocean currents, temperature, and salinity (Turner et al. 2015, p. 4; Trathan et al. 2020, p. 5). Therefore, sea ice extent and/or concentration can be a convenient correlation that is probably a proxy for other, more difficult to quantify factors and can reduce the number of correlated covariates (Trathan et al. 2020, p. 5; Grosbois et al. 2008, in Jenouvrier et al. 2012, p. 2766). Using sea ice extent or concentration as a proxy to describe the sea ice environment experienced by emperor penguins will provide an accurate depiction of the emperor penguin and its habitat now and into the future. Additionally, in Chapter 5: Projected Future Conditions section below, the modeling efforts attempt to project the sea ice conditions through the end of the century as it relates to the emperor penguin's habitat and population response.

Sea ice extent in the Southern Ocean undergoes considerable inter-annual variability, although with much greater inter-annual variability in the five sectors than for the Southern Ocean as a whole (Parkinson 2019, p. 14414; Turner et al. 2015, p. 9; Figures 4.2a-e). The satellite record (1979–present) reveals that the gradual, decades-long overall increase in Antarctic sea ice extent reversed in 2014, with subsequent rates of decrease in 2014–2017 far exceeding the more widely publicized decay rates experienced in the Arctic (Parkinson 2019, p. 14414). In 2017 and 2018, the average annual sea ice extent was the lowest in the entire 40-year record and essentially

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[7] Sea ice extent is the distance from the coast to the outermost edge of the ice pack (Ainley et al. 2010, p. 51) and defines a grid cells as ice covered or not, based on whether the cell is covered by at least 15% sea ice concentration (Jenouvrier et al. 2019, p. 6). If the cell has 15% or greater ice concentration, the entire cell is included as ice covered. Sea ice concentration is a unitless term that describes the percentage of a given area of ocean covered by ice. This measure is very (spatially) scale dependent and varies directly with sea ice extent at large scales (Ainley et al. 2010, p. 51). Sea ice area measures the percentages of sea ice within each grid cell and sums those areas where sea ice covers at least 15%. Extent is always a larger number than area (NSIDC 2020, unpaginated).

wiped out the overall increases from the previous years (Parkinson 2019, p. 14415). This record low sea ice extent likely affected breeding success at some colonies (Fretwell and Trathan 2019, Fretwell and Trathan 2020).

Overall, the yearly sea ice extent in the Southern Ocean, which includes the low sea ice years, has a positive overall trend over the last 40 years (11,300 +/- 5,300 km^2 y^{-1}; Parkinson 2019, p. 14414). Although the overall increase masks larger, opposing regional differences in trends (Turner et al. 2015, pp. 1–2; Parkinson 2019, p. 14419). The greatest increase in sea ice extent has been in the Ross Sea sector, and there have been smaller increases in the Weddell Sea and around the coast of East Antarctica, and a decrease in the Bellingshausen-Amundsen Sea sector in West Antarctica (Turner et al. 2015, p. 9; Holland 2014, in Meredith et al. 2019, p. 214; Parkinson 2019, entire). Figure 4.1 depicts the yearly average sea ice extent for the entire southern hemisphere.

Commented [HZ9]: Make sure to always be clear about what property of sea ice is increasing. In increase in extent does not necessarily mean an increase in sea ice thickness for example

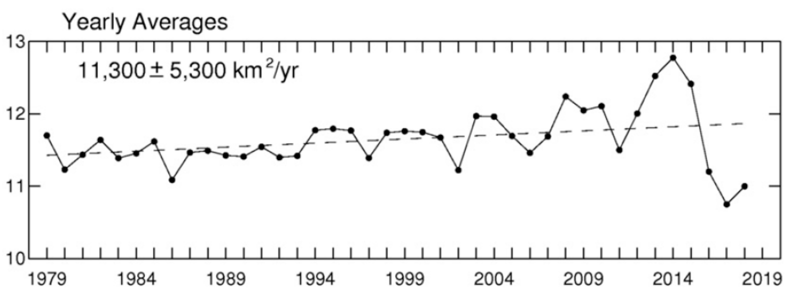


Figure 4.1. Yearly sea ice extent for the Southern Hemisphere. Y-axis is ice extent (10^6 km^2)

The positive trend in the Southern Ocean should not be unexpected despite climate change and the strong negative trend in the Arctic ice cover because the distribution of global surface temperature trend is not uniform (Comiso et al. 2017, p. 2265). The two Polar Regions are very different. In the Antarctic region the trend in surface temperature is about 0.1 °C decade^{-1} while the trend is 0.6 °C decade^{-1} in the Arctic and 0.2 °C decade^{-1} globally since 1981 (Comiso and Hall 2014, cited in Comiso et al. 2017, p. 2265). Additionally, the Southern Ocean and four of the five sectors—all except the Ross Sea—have experienced at least one period since 1999 when the yearly average sea ice extent decreased for three or more straight years only to rebound again afterward and eventually reach levels exceeding the sea ice extent preceding the 3 years of decreases. Therefore, the recent decrease in sea ice is no assurance of a long-term negative trend (Parkinson 2019, p. 14420).

Below are yearly averages of sea ice extent in the five sectors, including years (or months) of the high and low sea ice extent in the 40-year record (Parkinson 2019, pp. 14415–14419; Figures 4.2a-e, also see Figure 2.6 for boundaries of the five sectors discussed below):

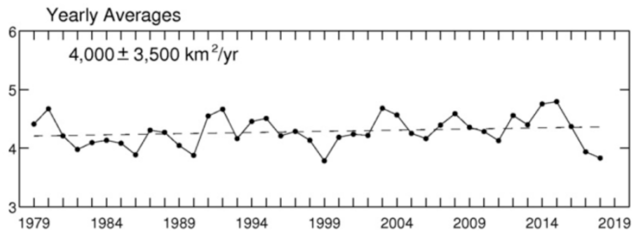


Figure 4.2a. Yearly sea ice extent for the *Weddell Sea* (10^6 km^2). The Weddell Sea overall increased on a yearly average basis through 2014, then markedly decreased 2015–2018, falling just short of the minimum yearly sea ice extent on record set in 1999. Record high sea ice extent occurred in September 1980.

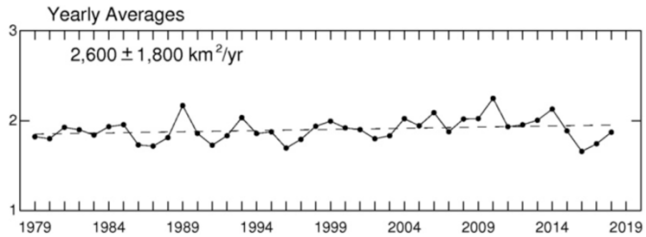


Figure 4.2b. Yearly sea ice extent for the *Indian Ocean* (10^6 km^2). The Indian Ocean record high occurred in October 2010. A decrease in yearly average sea ice extent from 2010–2011 was followed by a rebound in the next 3 years (2012–2014) and then a 2 year decrease (2015–2016) resulting in record minimum yearly sea ice extent in 2016, before rebounding somewhat in 2017 and 2018.

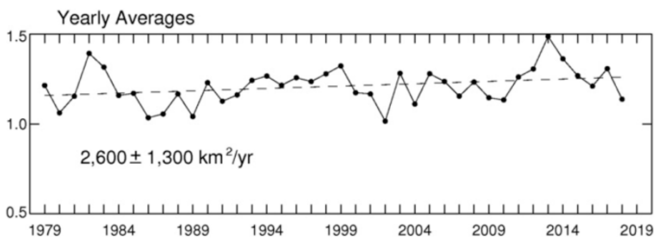


Figure 4.2c. Yearly sea ice extent for the *Western Pacific Ocean* (10^6 km^2). Western Pacific Ocean yearly sea ice extent increased overall until reaching the record high in 2013, followed by a prominent downward trend from 2013–2018. Lowest sea ice extent was in 2002.

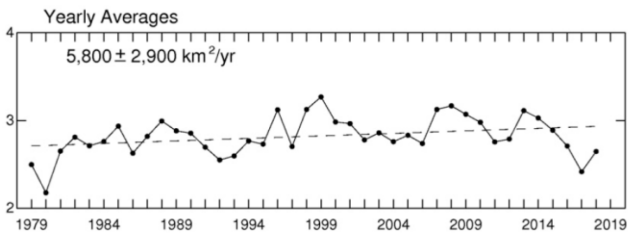


Figure 4.2d. Yearly sea ice extent for the *Ross Sea* (10^6 km^2). The Ross Sea overall, non-uniform reduction of sea ice coverage since the high in 2007 led to an almost total disappearance of the sea ice and record low in February 2017, with some rebounding the following year. The record high yearly value was in 1999.

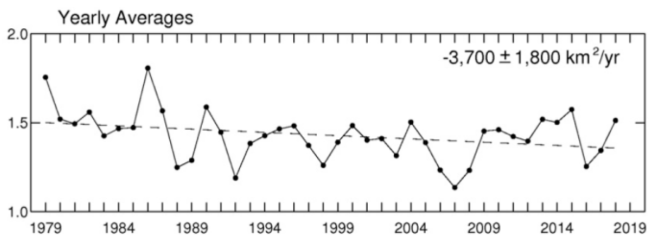


Figure 4.2e. Yearly sea ice extent for the *Bellingshausen-Amundsen Seas* (10^6 km^2). The Bellingshausen-Amundsen Seas sector is the most out of line with the rest of the Southern Ocean. The major contrast between the Bellingshausen-Amundsen Seas sector and the rest of the Southern Ocean is that it had an overall downward trend in ice extent for most of the record, followed by an overall upward trend. This corresponds well with the marked regional warming recorded on the Antarctic Peninsula, adjacent to the Bellingshausen Sea, for the early decades of the 40-year record. Warming occurred that has not been recorded elsewhere on the continent. The yearly average sea ice extent in the Bellingshausen-Amundsen Seas reached their minimum in 2007; although the upward trend since 2007 did not result in record high yearly sea ice extent.

Commented [HZ10]: My issue with this statement is that from the figure, the overall 40-year trend is negative, and the post-2007 positive trend is very hard to pick out by eye. Is there another figure that shows the post-2007 trend line as well?

Summary of Current Condition

The emperor penguin is a high latitude, sea ice obligate seabird that depends on the presence of sea ice to complete its annual breeding cycle. As of 2020, 61 breeding colonies are extant. Of the 66 total colonies ever known to exist, four were not extant in 2019, 1 colony is extirpated, and 11 of the colonies were newly discovered or rediscovered in 2019. The total population is approximately 270,000–280,000 breeding pairs.

Commented [HZ11]: Just a question: why do you refer to breeding pairs here as the 'total population' given that the total population consists of more than just breeding pairs?

Total Known Colonies	Extant Colonies in 2019	Colonies not Extant in 2019	Extirpated Colonies
66	61	4	1

Climate change is the only major threat that is affecting the entire range of the emperor penguin and each breeding colony. Warming air and sea temperatures in the Southern Ocean and around the continent of Antarctica will affect the extent and duration of sea ice and ~~relatedly~~ prey abundance because primary production and main prey resources are directly related to the extent and duration of sea ice. Emperor penguins may have difficulties finding food in years of low sea ice, which could increase mortality and reduce breeding success. Currently, prey abundance is not a limiting factor for the emperor penguin.

The Antarctic continent has seen less uniform temperature changes over the past 30–50 years and most of Antarctica has yet to see dramatic warming (Meredith et al. 2019, p. 212). The Antarctic Peninsula has warmed 2.5 °C since 1950, and there is no clear trend in East Antarctica. The consequences of these changes in climate are difficult to predict. Sea ice extent in the Southern Ocean has an overall positive trend but varies regionally, with strong declines in the Amundsen-Bellingshausen sector. The atmosphere and ocean have warmed, the amount of snow and ice has diminished, the cryosphere has shrunk with mass loss from ice sheets and glaciers, and sea level has risen (NASA 2020, unpaginated; IPCC 2014a, p. 2; IPCC 2019a, p. 6).

Commented [HZ12]: Yes this is true but how is it related to what you are specifically saying about Antarctica earlier in this paragraph?

Resiliency

As of 2020, emperor penguins are extant at 61 breeding colonies. The total population size is estimated to be 270,000–280,000 breeding pairs with the largest colonies in the Ross Sea and Weddell Sea. Current colony size ranges from 0–2000 to more than 16,000 breeding pairs (Table 2). *Aptenodytes* spp. generally have high breeding success, rearing on average 0.6–0.8 chicks per pair. However, as sea ice extent ~~may vary~~varies annually, emperor penguin breeding success may also vary, as was seen in the population at the Pointe Géologie colony. Breeding success ranged from 3–86% over six decades, ~~which included~~including a drastic population decline of 50% in the 1970s that coincided with the lowest sea ice extent recorded at that location. It is unknown if the breeding success variability is a regional signal or affects the continent as a whole (Fretwell 2012, p. 7). Colony size can fluctuate at individual colonies by as much as 30% and changes of more than 10% are typical (Fretwell et al. 2012, p. 9).

Commented [HZ13]: Over what time period? What is a typical length of time over which a colony might fluctuate 10%, for example, a year? Longer?

Sea ice extent in the Southern Ocean has a positive overall trend over the last 40 years (11,300 +/- 5,300 $km^2\ y^{-1}$), with greater variability within and among the five sectors. The overall trend includes the years of record sea-ice decline that occurred from 2014–2018. This decline of sea ice likely affected emperor penguins. Current sea ice conditions support 61 extant breeding colonies distributed around the continent of Antarctica. Four colonies were not extant in 2019, and one colony has been extirpated. Emperor penguins have continued to inhabit colonies that have experienced loss of sea ice for one or multiple breeding seasons (i.e., Cape Crozier, Pointe Géologie), although the size of the population at these colonies became smaller as the habitat quality decreased. Emperor penguins have also relocated to nearby colonies after the resident colony experienced total sea ice loss or sea ice does not remain for the entirety of the breeding season (i.e., Halley Bay to Dawson-Lambert). Overall, the emperor penguin has high resiliency because ~~current~~ sea ice conditions currently support 61 extant breeding colonies around the continent, even if colony size typically fluctuates at individual colonies annually.

Redundancy

The emperor penguin has high redundancy because the species is distributed around the entire continental coastline of Antarctica. Breeding colonies are circumpolar with the mean loxodromic distance between colonies of 311 km ± 176 km, and ranging between 19 and 899 km (Ancel et al. 2017, p. 173). The number of known colonies has increased over time because the use of satellite imagery has improved the ability to locate colonies and estimate population size.

Catastrophic events may include iceberg calving, ice shelf disintegration, or storm events. During any particular year, these events have the potential to destroy or alter fast ice where breeding is occurring at any time during the breeding season, which could preclude colony formation or lead to mortality of adults and/or total breeding failure once eggs or chicks are present and have not yet fledged (Ainley et al. 2010, p. 55). However, a catastrophic event would only affect a very small proportion of the total breeding colonies at any one time. Additionally, if a catastrophic event occurs, the species has been known to try to return to that same breeding location and/or relocate to another nearby site and reproduce the next breeding cycle (i.e., Halley Bay) (Fretwell and Trathan 2019, p. 3).

Representation

Representation for the emperor penguin is based on its ability to adapt to a changing environment. Genetic diversity exists between the Ross Sea colonies and other colonies around the continent. The four known metapopulations—distributed within some of the five sectors—have some degree of connectivity among the metapopulations and very high connectivity between breeding colonies within each of the known metapopulations (Younger et al. 2017, p. 3888; see Figures 2.1 and 2.6). Emperor penguins at many breeding colonies in the five sectors have not been genetically analyzed to determine if other metapopulations exist. However, the fact that emperor penguins travel widely as juveniles, move among breeding colonies and emigrate, and share molting locations indicates that dispersal is providing gene flow among populations. No gaps between emperor penguin colonies are greater than 500 km, except in front of large ice shelf fronts, which are probably areas of unsuitable habitat (Fretwell and Trathan 2020, p. 10).

All colonies follow the same annual schedule and the vast majority of breeding colonies occur on fast ice. Therefore, there is not a lot of ecological diversity between breeding locations of the emperor penguin. Colonies where penguins breed on ice shelves consist of marginal conditions of low mean sea ice and/or higher than average mean temperatures. It is unknown whether breeding on ice shelves is a new phenomenon associated with recent climate change and its effects on the presence of sea ice, or one that has always existed but is not well documented (Fretwell et al. 2014, p. 2). Ice shelves are less susceptible to local weather patterns and may provide security from decreasing sea ice (Fretwell et al. 2014, p. 2). However, breeding on an ice shelf is a high-risk strategy and it is unclear how emperor penguins get access to the top of an ice shelf because they are not agile on land, but may use snow ramps if available.

Emperor penguins can respond to climate change in two main ways, dispersal and adaptation (Forcada and Trathan 2009, p. 1624). When sea ice conditions are marginal or inadequate to complete breeding, emperor penguins may move onto land or ice shelves or relocate to higher quality sea-ice habitat. The adaptive capacity of emperor penguins is unknown, but the species has so far shown little evidence of adaptive capacity (Trathan et al. 2020, p. 7). The paleontological record for penguins shows that the most likely response to climate change is likely to be dispersal to new habitat (Forcada and Trathan 2009, p. 1626).

CHAPTER 5: PROJECTED FUTURE CONDITIONS

Much of the research into emperor penguin populations and their habitat conditions based on sea ice changes into the future is founded on standard climate modeling efforts (e.g., Ainley et al. 2010, Jenouvrier et al. 2012, 2014, 2017, 2019; Melillo et al. 2014). The future scenarios in which we summarize population projections for emperor penguins will be through the lens of these climate change projections and follow available scenarios. ~~Existing foundational work on sea~~Sea ice conditions (e.g., extent, concentration, duration) have been~~s~~ projected ~~out to the~~to the end of the 21st century (2100) using Global Circulation Models (GCMs) from the Coupled Model Intercomparison Project[8] (CMIP) phase 3 (CMIP3) and phase 5 (CMIP5)~~ ensemble models~~. The spatial resolution of ~~for~~ CMIP5 models has improved relative to CMIP3, but the overall improvement in performance is relatively minor. Certain variables, regions, and seasons show improvement; for other variables, there is no difference between outputs of the models (Hayhoe et al. 2017, p. 142). CMIP3 simulations are driven by SRES scenarios and CMIP5 simulations are driven by RCP scenarios (Hayhoe et al. 2017, p. 142).

Commented [HZ14]: Probably best to spell out these acronyms here because they are being introduced for the first time

Given the complexities of GCMs and advancements in technology, models typically build upon previous modeling efforts. In the case of modeling the emperor penguin population and sea ice, much of it under scenario SRES A1B, research was conducted using the best available information of the population and demographics at the time. As experts learned more information about emperor penguin dispersal capabilities and behavior~~,~~ and discovered more colonies that increased the total population size, the modeling efforts were refined to account for additional colonies and inter-colony dispersal behaviors~~ of emperor penguin~~.

Future Projections under a Low, Moderate, and High Emissions Scenario

We discuss three future scenarios in this section based on existing work projecting sea ice conditions and penguin response. We chose three projections out to the end of the 21st century based on a low, moderate, and high future emissions scenarios (USGS 2020, p.20), summarized in Table 6. ~~.~~

~~The model~~Model simulations for the Paris Agreement goals ~~would~~ represent a low emissions scenario that leads to the smallest temperature increase into the future because these scenarios are designed to~~forced to only~~ reach aa 1.5~~ or~~ or ~~-~~2 °C temperature increase by the end of the century (Jenouvrier et al. 2019, p. 1). The Paris Agreement goals do not represent or equivocate to any RCP scenario. They are unique scenarios that were designed explicitly to meet the global

[8] The Coupled Model Intercomparison Project (CMIP) is an international effort started in the 1990s by multiple research organizations to produce, study, and compare climate simulations. Coupled models refer to GCMs that include atmospheric and oceanic models. CMIP is led by the World Climate Research Programme and provides output from more than 50 GCMs. The CMIP output is the primary source of climate information used to project impacts of greenhouse gas emissions (USGS 2020, pp. 7–8).

temperature change targets set in the Paris Agreement (Sanderson and Knutti 2016, in Jenouvrier et al. 2019, p. 1). This is in contrast to other emissions scenarios—the SRES and the RCP scenarios used in the fourth and fifth IPCC assessment reports, respectively. While these scenarios consider a range of possible human activity and resulting greenhouse gas emissions, they had no explicit consideration of the Paris Agreement targets and hence do not lead to a 1.5 or 2 °C global average warming by 2100 (Jenouvrier et al. 2019, p. 3). However, the global temperature is likely to increase from 0.3–1.7 °C under RCP 2.6, and 1.0–2.6 °C under RCP 4.5 (IPCCb 2019, p. 46). Therefore, based strictly on the projected increase in global temperature, these Paris goals would fall at the high end of RCP 2.6 projections and within the projected range of RCP 4.5[9].

Most of the modeling efforts for penguin response to climate change have simulated sea ice conditions under SRES A1B, which is consistent with RCP 6.0 (Melillo et al. 2014, p. 755). The results of this scenario ~~would~~ represent a moderate emissions scenario ~~because~~ where global temperature is projected to increase up to 3 °C by the end of the century (IPCC 2019b, p. 46).

Using CMIP5 simulations, the emperor penguin populations and sea ice projections were also simulated under RCP 8.5, a high emissions scenario with the greatest warming, where global temperature is projected to increase by up to 5 °C (IPCC 2019b, p. 46). ~~Therefore, RCP 8.5 represents the high emissions scenario with the greatest warming, based on the simulations that have been conducted.~~

Table 6. Future Climate Scenarios Modeled for Emperor Penguins and Sea Ice

Scenario	**Global Temperature Increase by 2100**	**Rank**
Paris Agreement Goals (within the range of global temperature increases projected under RCP 2.6 and 4.5)	1.5–2 °C	Low
SRES A1B (RCP 6.0)	3 °C	Moderate
RCP 8.5	5 °C	High

Uncertainty

The future scenarios are based on model projections of sea ice in the Southern Ocean and surrounding the continent of Antarctica, and the emperor penguin's response to the projected change in sea ice. The output of the models and future projections depend on the climate change scenario analyzed as well as internal variability, and as a result projections from models ~~that are estimated from data~~ are always accompanied by uncertainty. To help account for scenario uncertainty in the analysis, we considered future conditions of sea ice and the response of emperor penguins based on climate change projections under a low, moderate, and high emissions (warming) scenario.

Commented [HZ15]: Also important is how well a particular model is at representing the current climate state, i.e. how biased it is. These biases matter for present day simulations and future projections. Strictly speaking this isn't *uncertainty* but it does matter for the results. May be good to add this here especially because it's discussed a bit later in this section

[9] We reached out to the researcher who developed many of the models used in this analysis to inquire about model projections under RCP 4.5. This climate change scenario has not been modeled (Jenouvrier 2020, pers. comm.).

Climate/Model Uncertainty

Uncertainty in century-scale projections of Earth's climate stems from three primary sources: (1) the natural variability in the climate system; (2) imperfect scientific knowledge about the response of the climate system to changes in greenhouse gas (GHG) emissions; and (3) uncertainty about future trajectories of GHG emissions resulting from future human actions and policy decisions. In the near term, natural climate variability is the largest source of uncertainty in climate projections. Over multi-decadal timescales (approximately the next 30 to 50 years), uncertainties among climate model outputs tend to be most influenced by our imperfect scientific knowledge of the climate system. Over longer timescales (approximately the next 60 to 100 years), human actions and decisions that affect global GHG emissions are the largest source of uncertainty in climate projections (USGS 2020, p. 14).

Atmospheric concentrations of GHGs in the near- and mid-term are determined primarily by current emissions and the average time it takes emitted molecules to break down chemically in the atmosphere. In the long term, human choices regarding economic development, changes in technology and population trends will determine emission levels. To account for this uncertainty, most global and regional climate assessments use climate model results from a range of emissions scenarios. The climate models used in national and global assessments simulate plausible and realistic representations of Earth's climate, but variations of initial conditions or model parameters and differences in how the models are developed and configured causes variation in model outputs, and ultimately affects the sensitivity of any given model to changes in atmospheric GHG concentrations (USGS 2020, p. 14).

The choice of spatial scales is an important issue in studies of climate change using GCMs that project sea ice variables such as concentration, thickness, and extent, over a greater spatial scale than the scale of emperor penguin habitat requirements (Jenouvrier et al. 2012, p. 2766). For emperor penguins, the size of polynyas, sea ice thickness, area of fast ice, the timing of ice formation and breakup are meaningful variables with respect to the penguin's life cycle~~,~~ but are measurable only at small spatial scales (Jenouvrier et al. 2012, p. 2766). Therefore, sea ice extent and/or concentration can be a convenient correlation that is probably a proxy for other, more difficult to quantify factors and can reduce the number of correlated covariates (Trathan et al. 2020, p. 5; Grosbois et al., 2008, in Jenouvrier et al. 2012, p. 2766).

The modeled projections of sea ice remain a key issue (Trathan et al. 2020, p. 5). The ensemble model simulations do not capture the historical sea ice extent because the mean across multiple models show a decrease in total Antarctic sea ice extent during the satellite era, in contrast to the lack of an observed trend (Meredith et al. 2019, p. 223). Models do not capture the regional and in some cases opposing trends of sea ice observed by satellites. The period of satellite observation is relatively short (four decades) ~~in order to~~ for ascertaining whether ~~the~~ models adequately ~~assess~~ simulate ~~the~~ internal variability at longer time scales (Hobbs et al. 2016, p. 1548). Overall, there is low confidence in projections of Antarctic sea ice because there are multiple anthropogenic forcings; complicated processes involving the ocean, atmosphere, and the adjacent ice sheet; and competing scientific explanations (Meredith et al. 2019, p. 205).

Commented [HZ16]: I think the connection between these two sentences needs to be clarified here, i.e., how do the authors of the cited studies make the connection between the small-scale observable quantities and the larger-scale (on the order of a model grid cell size) output provided by the models?

Ecological Uncertainty
Uncertainty exists regarding the use of demographic variables obtained from one colony and extrapolating those values across the entire population in order to run model simulations. The demographic parameters used for all colonies are based on, and extrapolated from, the population at the Pointe Géologie colony in Terre Adélie (Jenouvrier et al. 2014, entire). The vast majority of colonies will never be visited or part of long-term studies because they are not accessible. Therefore, demographic parameters must be based on an extension of the data from Pointe Géologie given the absence of demographic data from other colonies. However, this may give the benefit of the doubt to other colonies because sea ice conditions were close to optimal in Terre Adélie (Jenouvrier et al. 2014, p. 716).

Behaviors of emperor penguins in response to changing sea ice conditions have uncertainty. It is clear that emperor penguins depend on stable sea (fast) ice to form breeding colonies and lack of sea ice disrupts breeding success. It is unknown whether breeding on ice shelves (as sea ice conditions decline) is a new phenomenon associated with recent climate change or one that has always existed but not well documented (Fretwell et al. 2014, p. 2). Whether this behavior would provide temporary or permanent relief from a projected decrease in sea ice remains uncertain (Fretwell et al. 2014, p. 8; Wienecke et al. 2012, p. 1293). Additionally, the benefits of dispersal rate, direction, and distance are hard to predict as sea ice conditions decrease around Antarctica. No gaps between colonies are greater than 500 km, except in front of areas of unsuitable habitat, and a scenario in which all colonies are connected could be possible (Jenouvrier et al. 2017, p. 71). It is reasonable to assume that emperor penguins will at least attempt to disperse from lower quality habitat to higher quality habitat if sea ice conditions become worse over time in certain regions and at certain colonies.

The effect of climate change on marine life in the Southern Ocean could be substantial. However, the effect is difficult to determine because the time series data is insufficient to attribute a climate change signature and may be due to a combination of climate change and natural variability (Meredith et al. 2019, p. 230; Ainley et al. 2010, p. 63). Therefore, it is challenging to differentiate effects of climate change from other factors that may affect emperor penguin's prey base. Nevertheless, primary prey species of emperor penguin are tied to sea ice extent and duration, and the best available information projects that sea ice will decrease at a higher rate under higher emission scenarios than low or moderate emission scenarios.

Low Emissions Scenario – Paris Agreement Targets of 1.5 °C and 2 °C Temperature Increase

For this scenario, a model linking future sea ice conditions to the emperor penguin response model developed by Jenouvrier et al. (2010, 2012, 2014, 2017) was used. This scenario uses the output from the Community Earth System Model Large Ensemble project (CESM-LENS; Kay et al. 2015), which is a model that contributed to ~~the~~ CMIP5 and was included in the IPCC fifth assessment report (Jenouvrier et al. 2019, pp. 3–4). The Community Earth System Model has a good overall simulation of numerous aspects of the Antarctic climate, including historical sea ice conditions, except in a few regions and seasons (Jenouvrier et al. 2019, p.4). Simulations used large ensemble member runs from 1920–2100 with historical forcings over the 20th century and the emission scenarios that result in 1.5 °C or 2 °C global average temperature by 2100. The

Commented [HZ17]: I put the title of this paper in the excel spreadsheet!

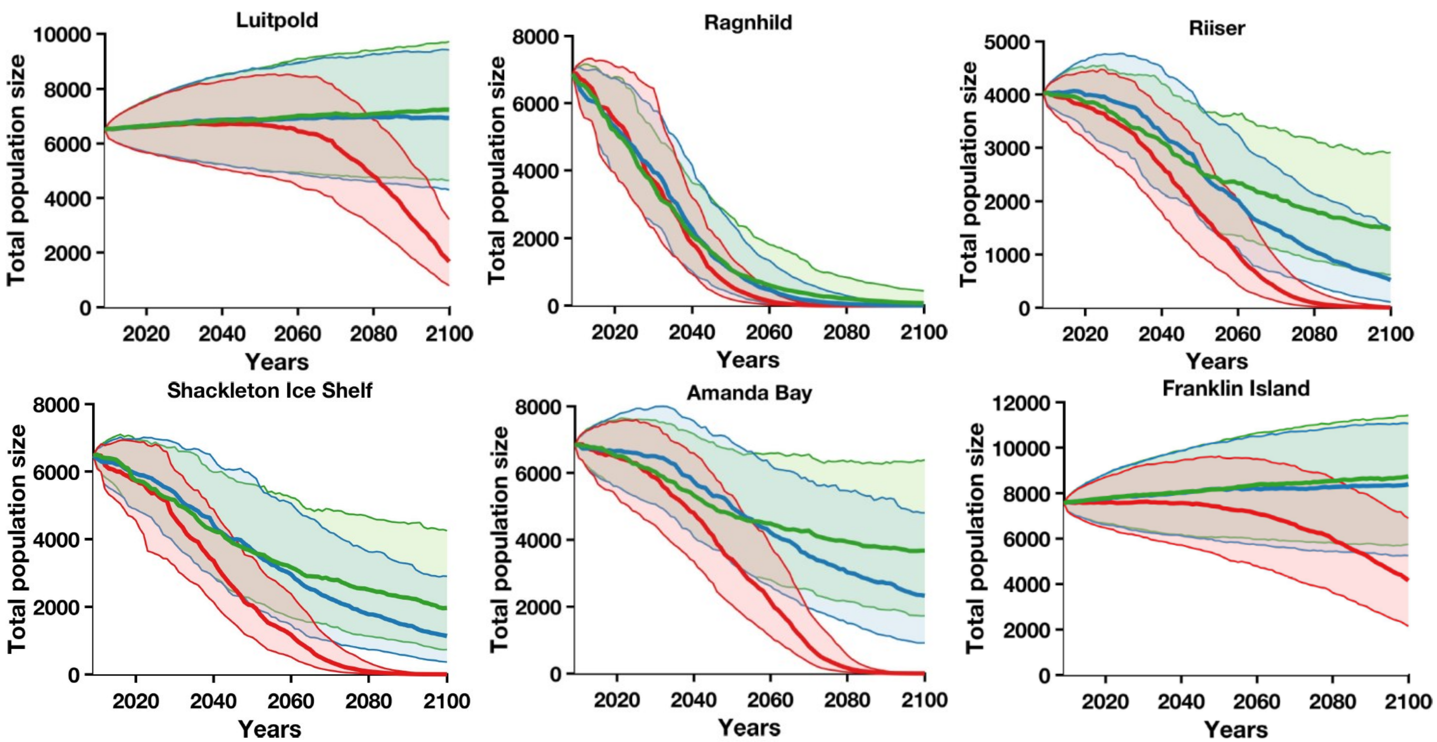
Commented [HZ18]: The CESM-LENS is not a model but rather a set of simulations done with a particular model, which is the CESM, so some rewording is needed here

Paris target simulations are branched from the CESM-LENS simulations in 2006 ~~,~~and run from 2006–2100. (Jenouvrier et al. 2019, p.4). Using a large ensemble of simulations allows an assessment of the internal variability of the model.

Resiliency

Under Paris 1.5 and Paris 2, large sea ice declines are limited to colonies in Dronning, Enderby, and Kemp Lands in the eastern Weddell Sea and Indian Ocean, with additional colonies included in the Bellingshausen and Amundsen Seas under Paris 2 (see Figure 5.1.3, below). Most colonies experience sea ice declines smaller than 10%~~,~~ relative to their historical mean during the breeding season under Paris 1.5 (except the colonies in Dronning, Enderby, and Kemp lands). Colonies that experience the largest decrease in population are located in eastern Antarctica in the sectors mentioned above and in the w~~W~~estern Pacific Ocean where projected sea ice declines are the largest, as well as in western Antarctica when accounting for the slight increase in warming from Paris 1.5 to Paris 2. Colonies in the Weddell Sea and Ross Sea are more likely to experience sea ice declines smaller than 10%~~,~~ relative to the historical mean during all four seasons of the emperor penguin's life cycle (Jenouvrier et al. 2019, p. 9). The colonies in the Ross Sea are projected to increase from their current size by 2100.

The figures below are representative of colonies in the regions discussed above. Starting from the Weddell Sea and moving clockwise,~~.~~ Luitpold is a colony in the western Weddell Sea. Ragnhild and Riiser are colonies in the eastern Weddell Sea and Indian Ocean on Dronning Maud and Enderby Lands that are projected to be have the least resiliency and decline by more than 90%. Shackleton Ice Shelf and Amanda Bay are representative of colonies in the southern Indian Ocean and w~~W~~estern Pacific Ocean that decline by more than 50%. Franklin Island is in the Ross Sea. The colonies in the western Weddell Sea and Ross Sea have the highest resiliency because these areas are likely to have the best sea ice conditions in the long term. All of these colonies in the figures are estimated to contain approximately 4,000–8,000 breeding pairs (Table 7). The last three colonies span the range of the Bellingshausen and Amundsen Seas. Colonies in this region show variability in their resiliency as some colonies are likely to decline by more than 90% and others ~~only~~ by more than 50% (Figure 5.1.3).


Luitpold
Ragnhild
Riiser
Shackleton Ice Shelf
Amanda Bay
Franklin Island
Total population size
Years
0
2000
4000
6000
8000
10000
12000
1000
3000
5000
2020
2040
2060
2080
2100

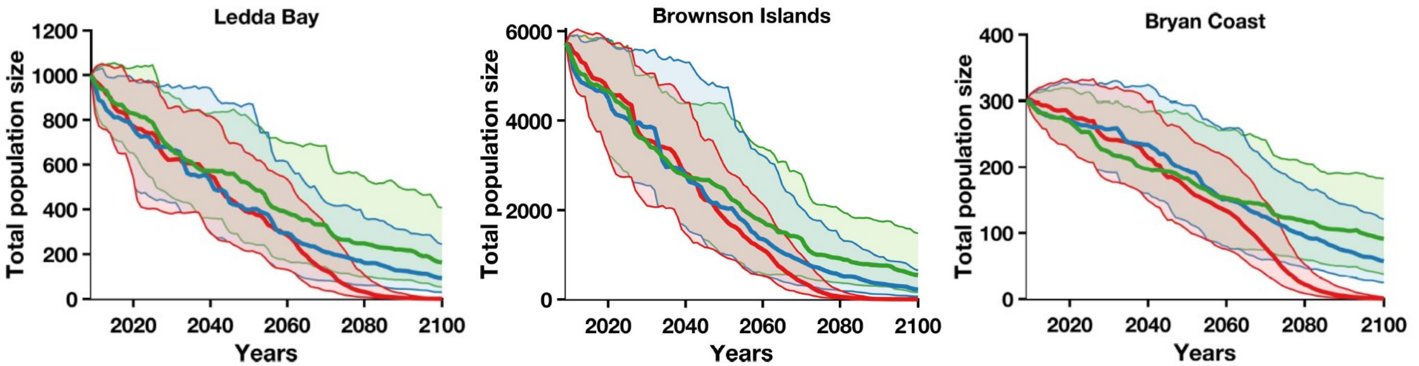


Figure 5.1.1. Luitpold (#6), Ragnhild (#16), Gunnerus (Riiser Larsen Peninsula; #17), Shackleton (#30), Amanda Bay (#25), Franklin Island (#42), Browson Islands (# 50), Ledda Bay (# 47), Bryan Coast (#52; Jenouvrier 2019b, entire). See Figure 2.10 and Table 2 for colony numbers and location.

Overall, the annual mean sea ice loss is 5% for Paris 1.5 and 13% for Paris 2, and the median total population size is projected to decline by 31% under Paris 1.5, and by 44% under Paris 2, without considering dispersal behavior. Despite the decline in abundance, population growth rates are projected to stabilize by 2100 such that the population will only be declining at 0.07% under Paris 1.5, and 0.34% under Paris 2 (Jenouvrier et al. 2019, p. 10). By including all uncertainties, the 90% confidence envelope of the population by 2100 ranges from a decline of 39% to an increase of 161% under Paris 1.5, and decline of 49% to an increase of 89% under Paris 2, respectively, relative to the 2010 initial global population size (see Figure 5.1.2) (Jenouvrier et al. 2019, p.10). Accounting for uncertainty in the model, the range of possibilities shows that the population may increase, but declines are more likely (Jenouvrier et al. 2019, p. 11).

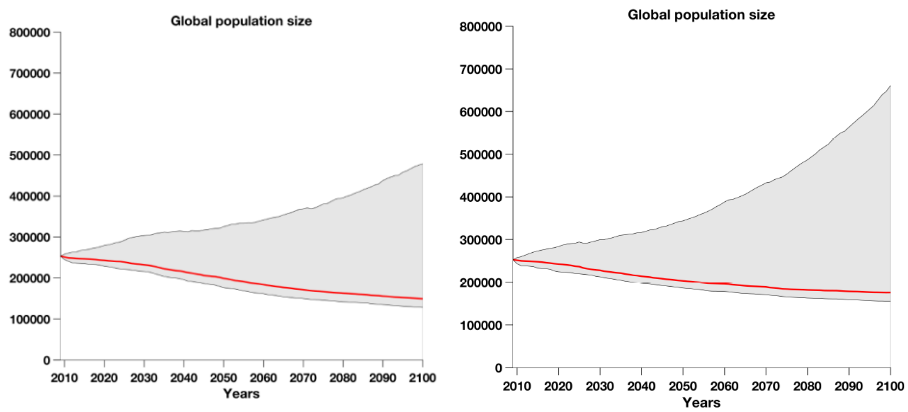


Figure 5.1.2. (a) Global number of breeding pairs of emperor penguins from 2010 to 2100 projected accounting for structural model uncertainties of demographic models. The global population size is calculated using sea ice concentration anomaly projections from the CESM using climate simulations under Paris 2 (left) and Paris 1.5 (right). The thick red line is the median with the gray area the 90% envelope from simulations of population trajectories (Jenouvrier et al. 2019b, pp. 172–173).

Redundancy

Under Paris 1.5 and Paris 2, the redundancy will decrease because the colonies in the eastern Weddell Sea and Indian Ocean—Dronning, Enderby, and Kemp Lands—are likely to be reduced by more than 90%, if not disappear by the end of the century due to poor sea ice conditions (see Figure 5.1.3). Emperor penguins at colonies with poor quality habitat may migrate to higher quality habitat as sea ice conditions decline at certain colonies or regions. Under Paris 1.5 and Paris 2, the probability was calculated for the decline in the number of breeding pairs at each colony by more than a specified threshold by 2100 (Jenouvrier et al. 2014, 2017). A likely outcome is a probability greater than 66%, which is used to attribute conservation status. A likely outcome is defined by the IPCC as a term to indicate the assessed likelihood of an outcome or a result (likely 66–100%; IPCC 2014a, p. 2). The newly discovered and/or rediscovered colonies and the Sabrina Coast colony are not included in the projections. The conservation status was defined:

Commented [HZ19]: Do we know how migration of penguins from a poor habitat to a better habitat stresses/impacts the environment of penguins in the higher quality habitat? What I am wondering is what happens if an entire population has to be displaced, and they happen to find their way to another colony with a better habitat? Can too many penguins in one area cause problems for breeding ground availability and/or food?

- Stable is a population decline by less than 30%,
- Vulnerable is a population decline by more than 30%,
- Endangered is a population decline by more than 50%, and
- Quasi-extinct is a population decline by more than 90%.

The probability of breeding pair declines were calculated for fifty-four (54) colonies. For Paris 1.5, 33 of 54 (61%) colonies in the eastern Weddell Sea, Indian Ocean, and West Pacific Ocean, from Dronning Maud Land and throughout eastern Antarctica to Terre Adélie Land; and Bellingshausen and Amundsen Seas are likely to decline by more than 30%. Fifty-four percent of colonies (29 of 54) are likely to decline by more than 50%. These colonies are from the same regions. Nineteen percent (10 of 54) of the colonies, mostly located in the eastern Weddell Sea and Indian Ocean, as well as two colonies in western Antarctica in the Bellingshausen and Amundsen Seas region, are likely to decline by more than 90% (Figure 5.1.3; Tables 7 and 10).

For Paris 2, similar patterns of the colonies' status emerge. Although, because the global temperature would be higher by 0.5 °C, more colonies decline compared to Paris 1.5. Projections show 67% of colonies (36 of 54) are likely to decline by more than 30% and these same colonies, except the Jason Peninsula and Stancomb Wills Glacier colonies, are likely to decline by 50%. The 31% (17 of 54) of colonies likely to decline by more than 90% occur in the same regions as under Paris 1.5 (eastern Weddell Sea, Indian Ocean, West Pacific Ocean, and Bellingshausen and Amundsen Seas). However, a few more colonies in the Bellingshausen and Amundsen Seas are likely to decline by more than 90% under Paris 2. The probability values of likely declines at each colony for Paris 1.5 and Paris 2 are below.

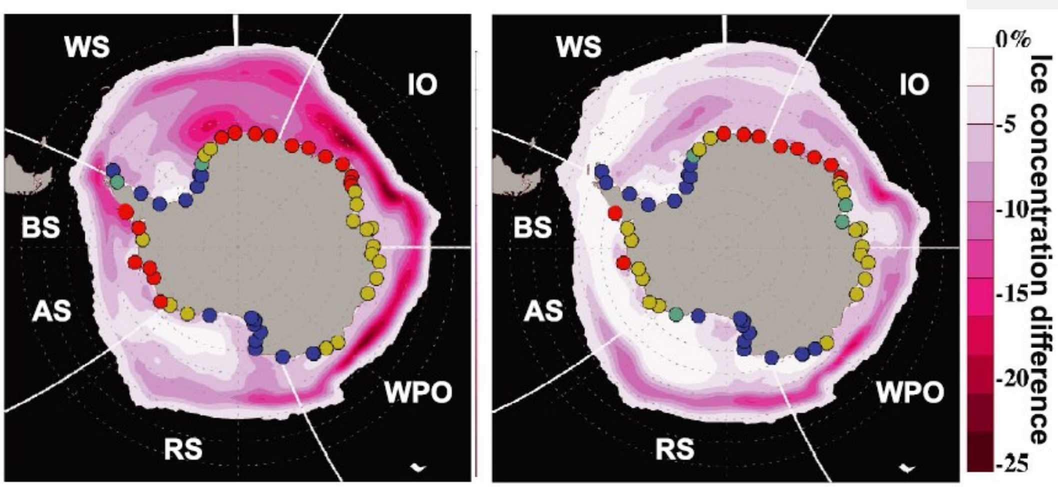


Figure 5.1.3. Annual mean change of SIC between 20th and 21st centuries and conservation status of emperor penguin Paris 2 (left), Paris 1.5 (right). The conservation status is: red = quasi-extinct – a population decline by more than 90%; yellow = endangered – a population decline by more than 50%; green = vulnerable – a population decline by more than 30%; and blue = a population

decline by less than 30%. Note that this figure is based on simulations that did not include dispersion (Jenouvrier et al. 2019, p. 9). WS=Weddell Sea, IO=Indian Ocean, WPO=Western Pacific Ocean, RS=Ross Sea, BS-AS=Bellingshausen and Amundsen Seas.

Representation

The vast majority of emperor penguin breeding colonies occur on fast ice. By 2100, under Paris 1.5 and Paris 2, annual mean Antarctic sea ice is projected to decline by 5% and 13%, respectively. The most threatened colonies are located in eastern Antarctica where projected sea ice declines are the largest. Emperor penguins may migrate to colonies with available habitat under these scenarios, as large sea ice declines are limited to fewer colonies in the eastern Weddell Sea and Indian Ocean on Dronning Maud, Enderby, and Kemp Lands, as well as a few colonies in the Bellingshausen and Amundsen Seas. Most other colonies experience sea ice loss less than 10% of their historical mean under Paris 1.5. A similar pattern emerges for Paris 2, although a few more colonies in the Bellingshausen and Amundsen Seas region will have reduced sea ice conditions and smaller population sizes.

The emperor penguin would lose some genetic diversity because the overall population abundance is projected to decline. Under Paris 1.5 and Paris 2, colonies that are part of each of the four known metapopulations decline but are projected to remain, although the colonies in the Mawson Coast metapopulation are projected to decline by more than 90% under Paris 2. Therefore, there is no loss of the known metapopulations under Paris 1.5, and only the likely decline of the colonies that make up the Mawson Coast metapopulation by more than 90% under Paris 2. The colonies that are projected to decline the most are in regions that were not part of the genetic analysis that identified the four currently known metapop~~o~~ulations. Emperor penguins from other colonies may migrate to the high quality breeding colonies as climate change reduces habitat around the continent. However, by the end of the century, the colonies that remain have likely reached carrying capacity.

Table 7. Conservation Status/Probability of Decline of the Emperor Penguin Colonies under Paris 1.5, and Paris 2. Colony No. is relative to Figure 5.1.3 (same as Figure 2.10).

<table>
<tr><th colspan="7">Conservation Status Paris 1.5</th></tr>
<tr><th>Colony Name</th><th>Colony No.</th><th>Sector</th><th>Vulnerable >30%</th><th>Endangered >50%</th><th>Quasi-extinct >90%</th><th>Population Size (2019)</th></tr>
<tr><td>Snow Hill</td><td>1</td><td rowspan="5">Weddell Sea</td><td>0.2394</td><td>0.0308</td><td>0</td><td>2000-4000</td></tr>
<tr><td>Jason Peninsula (Larsen Ice Shelf)</td><td>2</td><td>0.452</td><td>0.0962</td><td>0</td><td>0-2000</td></tr>
<tr><td>Dolleman Island</td><td>3</td><td>0.3418</td><td>0.06</td><td>0</td><td>2000-4000</td></tr>
<tr><td>Smith Peninsula</td><td>4</td><td>0.2222</td><td>0.0344</td><td>0</td><td>2000-4000</td></tr>
<tr><td>Gould Bay</td><td>5</td><td>0.071</td><td>0.0054</td><td>0</td><td>4000-8000</td></tr>
</table>

Luitpold Coast	6		0.0968	0.0062	0	4000-8000
Halley Bay	7		0.1606	0.0174	0	8000-12000
Dawson-Lambert Ice Tongue	8		0.154	0.0166	0	12000-16000
Stancomb-Wills Glacier	9		0.3918	0.0844	0	4000-8000
Drescher Inlet	10		0.7356	0.3218	0	8000-12000
Riiser Larsen Ice Shelf	11		0.9726	0.8166	0.0112	8000-12000
Atka Bay/Atka	12		1	0.9934	0.4022	4000-8000
Sanae	13		1	0.9996	0.7736	2000-4000
Astrid Coast Ice Tongue	14		1	1	0.943	0-2000
Lazarev Ice Shelf/Lazarev	15		1	0.9998	0.8914	0-2000
Ragnhild Coast	16	Indian Ocean	1	1	0.986	4000-8000
Gunnerus (Riiser Larsen Peninsula)	17		1	1	0.9998	4000-8000
Umbeashi Rock (Umebosi)	18		1	1	1	0-2000
Amundsen Bay	19		1	1	1	0-2000
Kloa Peninsula/Point	20		1	1	0.881	2000-4000
Fold Island	21		1	0.9988	0.464	0-2000
Taylor Glacier	22		0.9998	0.987	0.2008	0-2000
Auster	23		0.9738	0.8166	0.0082	4000-8000
Cape Darnley	24		0.696	0.2562	0	2000-4000
Amanda Bay	25		0.8794	0.5318	0.0004	4000-8000
Barrier Bay	26		0.9884	0.8704	0.0366	0-2000
West Ice Shelf	27		0.9828	0.8586	0.0306	0-2000
Burton Ice Shelf	28		0.9656	0.7918	0.0108	0-2000
Haswell Island	29	Western Pacific Ocean	0.9792	0.852	0.0236	2000-4000
Shackleton Ice Shelf	30		0.9858	0.8928	0.0376	4000-8000

Bowman Island	31		0.9606	0.7684	0.0034	0-2000
Petersen Bank	32		0.9962	0.9474	0.0852	2000-4000
Sabrina Coast	33					0-2000
Dibble Glacier	34		0.9512	0.7272	0.0056	12000-16000
Pointe Géologie	35		0.5854	0.1792	0	2000-4000
Mertz Glacier West	36		0.2686	0.037	0	2000-4000
Mertz Glacier East (Break Off)	37		0.2486	0.0412	0	4000-8000
Davis Bay	38		0.222	0.0264	0	0-2000
Cape Roget	39	Ross Sea	0.1074	0.0096	0	8000-12000
Coulman Island	40		0.113	0.009	0	16000+
Cape Washington	41		0.1132	0.011	0	8000-12000
Franklin Island	42		0.0714	0.0052	0	4000-8000
Beaufort Island	43		0.0658	0.0054	0	0-2000
Cape Crozier	44		0.0718	0.0068	0	0-2000
Cape Colbeck	45		0.1728	0.0242	0	16000+
Rupert Coast	46		0.8878	0.5898	0.0008	0-2000
Ledda Bay	47		0.9992	0.9878	0.2426	0-2000
Mount Sipple (Thurston Glacier)	48	Bellingshausen-Amundsen Seas	0.9998	0.999	0.5506	2000-4000
Bear Peninsula	49		0.9998	0.998	0.3622	8000-12000
Brownson Islands	50		0.9998	0.994	0.5506	4000-8000
Noville Peninsula	51		1	1	0.8954	2000-4000
Bryan Coast	52		0.9958	0.9216	0.0254	0-2000
Smyley Island	53		1	0.995	0.356	2000-4000
Rothschild Island	54		1	1	0.999	0-2000

Conservation Status Paris 2						
Colony Name	**Colony No.**	**Sector**	**Vulnerable >30%**	**Endangered >50%**	**Quasi-extinct >90%**	**Population Size (2019)**
Snow Hill	1	Weddell Sea	0.3612	0.0786	0	2000-4000
Jason Peninsula (Larsen Ice Shelf)	2		0.6852	0.2912	0	0-2000
Dolleman Island	3		0.5396	0.1704	0	2000-4000
Smith Peninsula	4		0.3158	0.0626	0	2000-4000
Gould Bay	5		0.0856	0.0106	0	4000-8000
Luitpold Coast	6		0.1196	0.0142	0	4000-8000
Halley Bay	7		0.3086	0.0628	0	8000-12000
Dawson-Lambert Ice Tongue	8		0.2574	0.0392	0	12000-16000
Stancomb-Wills Glacier	9		0.735	0.3666	0	4000-8000
Drescher Inlet	10		0.9686	0.8232	0.04	8000-12000
Riiser Larsen Ice Shelf	11		0.9992	0.9914	0.3842	8000-12000
Atka Bay/Atka	12		1	1	0.927	4000-8000
Sanae	13		1	1	0.9878	2000-4000
Astrid Coast Ice Tongue	14		1	1	0.9972	0-2000
Lazarev Ice Shelf/Lazarev	15		1	1	0.9974	0-2000
Ragnhild Coast	16	Indian Ocean	1	1	1	4000-8000
Gunnerus (Riiser Larsen Peninsula)	17		1	1	1	4000-8000
Umbeashi Rock (Umebosi)	18		1	1	1	0-2000
Amundsen Bay	19		1	1	1	0-2000
Kloa Peninsula/Point	20		1	1	1	2000-4000
Fold Island	21		1	1	0.9928	0-2000

Taylor Glacier	22		1	1	0.9624	0-2000
Auster	23		1	0.999	0.5432	4000-8000
Cape Darnley	24		0.967	0.7918	0.0156	2000-4000
Amanda Bay	25		0.9692	0.8184	0.0196	4000-8000
Barrier Bay	26		0.9966	0.9718	0.306	0-2000
West Ice Shelf	27		0.9986	0.9774	0.3274	0-2000
Burton Ice Shelf	28		0.99	0.9258	0.0844	0-2000
Haswell Island	29	Western Pacific Ocean	0.9966	0.9652	0.1402	2000-4000
Shackleton Ice Shelf	30		0.9994	0.9794	0.209	4000-8000
Bowman Island	31		0.9986	0.971	0.0944	0-2000
Petersen Bank	32		0.9998	0.9968	0.4106	2000-4000
Sabrina Coast	33					0-2000
Dibble Glacier	34		0.9994	0.996	0.332	12000-16000
Pointe Geologie	35		0.9438	0.714	0.0036	2000-4000
Mertz Glacier West	36		0.6472	0.2212	0	2000-4000
Mertz Glacier East (Break Off)	37		0.5952	0.1888	0	4000-8000
Davis Bay	38		0.4114	0.09	0	0-2000
Cape Roget	39	Ross Sea	0.1626	0.0214	0	8000-12000
Coulman Island	40		0.1702	0.0232	0	16000+
Cape Washington	41		0.1998	0.248	0	8000-12000
Franklin Island	42		0.096	0.0124	0	4000-8000
Beaufort Island	43		0.1164	0.0088	0	0-2000
Cape Crozier	44		0.085	0.0056	0	0-2000
Cape Colbeck	45		0.2956	0.0516	0	16000+
Rupert Coast	46		0.9814	0.847	0.0166	0-2000
Ledda Bay	47		1	1	0.5692	0-2000
Mount Sipple (Thurston Glacier)	48	Bellingshausen-	1	1	0.837	2000-4000

		Amundsen Seas				
Bear Peninsula	49		1	0.9998	0.723	8000-12000
Brownson Islands	50		1	1	0.9282	4000-8000
Noville Peninsula	51		1	1	0.9996	2000-4000
Bryan Coast	52		0.9998	0.9896	0.1086	0-2000
Smyley Island	53		1	1	0.7684	2000-4000
Rothschild Island	54		1	1	1	0-2000

Moderate Emissions Scenario – Special Report on Emission Scenarios A1B

In 2012, the emperor penguin population at Dumont D'Urville, in Terre Adélie (Pointe Géologie colony) and sea ice was modeled based on an ensemble from 20 CMIP3 models that were available. However, only a subset the GCMs were used because models vary in their ability to represent or match the historical sea ice record of Antarctica that has been observed through satellite imagery. See *Case Study –Pointe Géologie colony at Terre Adélie* above, for more discussion of this modeling effort.

In 2014, a population viability analysis for 45 emperor penguin colonies known at the time was conducted by forcing a sea-ice-dependent demographic model with local, colony-specific, sea ice conditions projected through the end of the 21st century. To project population dynamics of emperor penguins under climate change, a demographic model was driven with stochastic projections of sea ice anomalies. A sea ice anomaly is ~~, which is~~ the difference between the value of a sea ice ~~values~~ property (area, extent, or concentration) at a given time and its~~the~~ long-term average (NSIDC 2020, unpaginated). Anomalies have positive values where there is more ice than average and negative values where there is less ice than average (NSIDC 2020, unpaginated).

Commented [HZ20]: This might serve better as a footnote

Simulations in 2014 used multiple methods for sea ice projections, differing in the GCMs selected to run the projections of sea ice and emperor penguin response. There was no single model that matched the observed conditions at all colonies (Jenouvrier et al. 2014b, pp. 14–18). Subsequent modeling efforts (2017) enhanced model projections by including variables of dispersal behavior and density-dependent dispersion rates based on emperor penguin genetics (Cristofari et al. 2016; Younger et al. 2015), foraging ecology (Thiebot et al. 2013), and movement between colonies (LaRue et al. 2015).

To project future changes in the global penguin population, the median and 90% confidence interval were calculated. For each simulation, the number of breeding pairs relative to the starting population in 2010 was calculated, as well as the one-year growth rates of the breeding population for each year. All simulations were forced with the middle range emissions scenario––SRES A1B (Jenouvrier et al. 2014b, p. 28).

Resiliency

Similar to the projections under Paris 1.5 and 2, the emperor penguin colonies located in Dronning Maud, Enderby, and Kemp Lands in the eastern Weddell Sea and Indian Ocean are expected to decline the most and experience the largest declines and highest variability in sea ice. The Weddell Sea and Ross Sea colonies experience the smallest decrease in population abundance, and smallest decline and lowest variability in sea ice.

Projected changes in other regions are more complex ~~and vary according to seasons and regions~~. For example, under this moderate scenario, emperor penguin colonies in the Bellingshausen-Amundsen Seas are projected to fare slightly better than under the lower emissions scenarios of Paris 1.5 and 2. On the contrary, colonies in the Weddell Sea fare better under Paris 1.5 and Paris 2 than under this moderate scenario. Under the moderate scenario, most colonies (4 of 5) in the Bellingshausen-Amundsen Seas sector are likely to decline by more than 30%; the other colony is likely to decline by more than 50%. However, under Paris 1.5, most (6 of 8) colonies are likely to decline by more than 50% and two colonies are likely to decline by more than 90%. Further, under Paris 2, two colonies are likely to decline by more than 50% and most (6 of 8) colonies are likely to decline by more than 90% and (see Figures 5.1.3 and 5.2.2 for comparison). However, in the Weddell Sea, five colonies are likely to decline by less than 30% under Paris 1.5 and Paris 2, but under this moderate scenario only one of those five colonies is likely to decline by less than 30%, three are likely to decline by more than 30%, and one by more than 50%. Note that more colonies are analyzed under Paris 1.5 and Paris 2 as more colonies have been discovered by satellite over time.

Overall, the model projections indicate that sea ice will generally decline and its variability will increase by 2100. These future reductions differ regionally, among seasons and among different breeding colonies, with some experiencing large negative trends, while others experience better sea ice conditions with a potential decline in sea ice after mid-century (Jenouvrier et al. 2014b, pp. 18–19). The Antarctic is becoming a poor environment for emperor penguins as soon as 2036. Dispersal behaviors may serve as an 'ecological rescue' by delaying the population decline for about 10 years, from 2036 to 2046, depending on the carrying capacity of the most favorable colonies and the probability of settlement in better habitat. However, this effect is temporary because the colonies with good sea ice conditions quickly reach their carrying capacity. By mid-century (2050), the population is declining and less colonies remain favorable. Dispersal behaviors may accelerate, slow down, or reverse the anticipated rate of population decline of the emperor penguin, compared to the population projection without dispersal considered. Nevertheless, by the end of the century, no colonies are favorable and most are declining. The Ross Sea colonies will likely be the last potential refuge for the species (Jenouvrier et al. 2014a, entire; Jenouvrier et al. 2014b, entire).

Commented [HZ21]: Everywhere in the Antarctic? This is a very broad statement and could probably use some qualifiers

By 2100, the population is projected to decline by 78%, with a 3.2% decline in the annual growth rate. The population growth rate is mostly positive for the first 30 years but all colonies become negative by 2080. The Ross Sea populations are projected to increase and experience the least sea ice loss. However, even the Ross Sea colonies are declining by the end of the century. Colonies equatorward of 70 °S latitude have a 46–65% risk to decline by more than 90% (Jenouvrier et al. 2014, p. 716). A previous pan-Antarctic study suggested that sea ice was projected to decline, reduce emperor penguin habitat, and half of the colonies northward of 70 °S latitude would be jeopardized; however, this study did not provide estimates of population size or trends (Ainley et al. 2010, entire; Jenouvrier et al. 2014, p. 716). The global population size is larger when projected by a model that includes certain dispersal behaviors than a model without dispersion. Overall, dispersal behaviors (e.g., informed search) may increase the population size by 31%. However, other dispersal behaviors (e.g., random search and long distance dispersal) increase the probability that emperor penguins move to lower quality habitat that results in a population decrease of 65% by the end of the century (Jenouvrier et al, 2017, pp. 71–72).

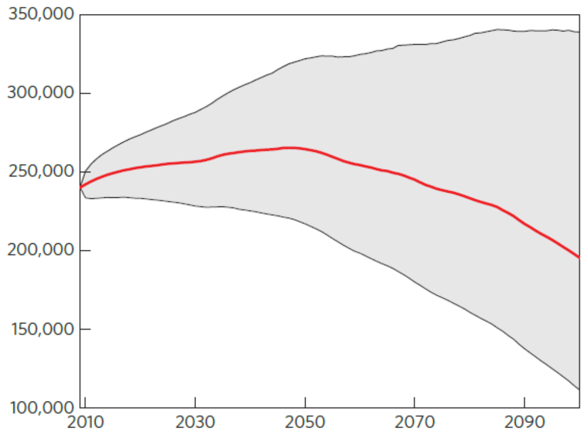


Figure 5.2.1. Global number of breeding pairs of emperor penguins from 2009 to 2100. The red line is the median and the grey area is the 90% envelope from stochastic simulations of population trajectories, without dispersal considered (Jenouvrier et al. 2014, p. 717).

Redundancy

Under this scenario, the redundancy of the emperor penguin will decrease as colonies in the eastern Weddell Sea and Indian Ocean in Dronning Maud, Enderby, and Kemp Lands are likely going to be reduced significantly, if not disappear, by the end of the century due to poor sea ice conditions (Figure 5.2.2). Emperor penguins have the ability to disperse and relocate to higher quality habitat. However, by the end of the century, the sea ice conditions are increasingly declining for emperor penguins and any colonies remaining have likely reached carrying capacity. Under SRES A1B, the probability was calculated for the number of breeding pairs that decline by more than a specified threshold by 2100 (Jenouvrier et al. 2014, 2017). The likely outcome is defined the same way as it was in the low emissions scenario.

The probability of breeding pair declines were calculated for forty-five (45) colonies. Seventy-six percent (34 out of 45) of the colonies are likely to decline by 30%. The majority of the colonies, 62% (28 out of 45), are likely to decline by more than 50%, and 20% (9 out of 45) of the colonies are likely to decline by more than 90%, relative to the current population size (Figure 5.2.2; Tables 8 and 10).

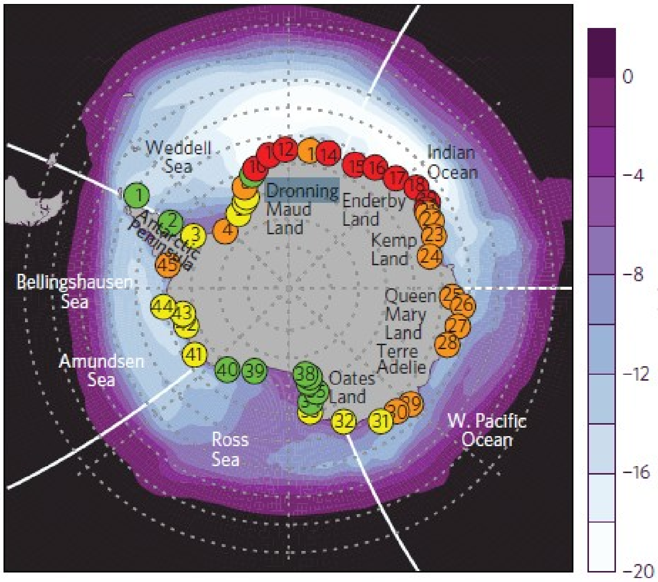


Figure 5.2.2. Annual mean change (%) of sea ice between 20th and 21st centuries and conservation status of emperor penguin (local analysis). The conservation status is based on IUCN criteria and definitions. Red refers to quasi-extinct – a population decline by more than 90%; orange is endangered – a population decline by more than 50%; yellow is vulnerable – a population decline by more than 30%; and green is not threatened. Note that this figure is based on simulations that did not include dispersion (Jenouvrier et al. 2014, p. 716).

Representation

The emperor penguin may lose genetic diversity with the likely decline of the breeding colonies in the eastern Weddell Sea and Indian Ocean by more than 90%. Additionally, other colonies in East Antarctica are projected to decline by more than 50%. These areas account for two of the four known metapopulations. The Ross Sea colonies are genetically distinct from other colonies around the continent, account for approximately 25% of the total population, and most likely will be the last potential refuge at the end of the century (Ainley et al. 2010; Jenouvrier et al. 2014; Jenouvrier et al. 2017; Younger et al. 2015, p. 2219; Younger et al. 2017, p. 3893). Emperor penguins from other colonies may migrate to the Ross Sea as climate change reduces sea ice around the continent. However, by the end of the century, the colonies that remain have likely reached carrying capacity and provide little potential for population expansion because of limited breeding area and unstable breeding habitat (Jenouvrier et al. 2014, p. 716). Therefore, the genetic diversity of emperor penguins will decrease because many of the breeding colonies that form the Mawson Coast and Amanda Bay/Point Géologie metapopulations, along with unanalyzed colonies in the eastern Weddell Sea and Indian Ocean regions, are going to be substantially reduced.

Table 8. Conservation Status/Probability of Decline of the Emperor Penguin Colonies under the moderate scenario. Colony No. is relative to Figure 5.2.2. Bolded numbers represent colonies that have a reduced conservation status under the moderate scenario compared to the low emissions scenario Paris 1.5. ** represents reduced conservation status under moderate scenario compared to Paris 2. Green font represents colonies that have an improved conservation status compared to the low emissions scenarios Paris 1.5 and 2. * represent colonies with the same conservation status under moderate scenario and low emissions scenario Paris 2, but not Paris 1.5.

Conservation Status SRES A1B						
Colony Name	**Colony No.**	**Sector**	**Vulnerable >30%**	**Endangered >50%**	**Quasi-extinct >90%**	**Population Size (2019)**
Snow Hill	1	Weddell Sea	0.55	0.0308	0	2000-4000
Dolleman Island	2		0.48	0.32	0.01	2000-4000
Smith Peninsula	3		**0.75**	0.63	0.01	2000-4000
Gould Bay	4		**0.88**	**0.78**	0.50	4000-8000
Luitpold Coast	5		**0.75**	0.60	0.31	4000-8000
Halley Bay	7		**0.74**	0.63	0.41	8000-12000
Dawson-Lambert Ice Tongue	6		**0.66**	0.56	0.29	12000-16000
Stancomb-Wills Glacier	8		**0.93**	**0.86**	0.42	4000-8000
Drescher Inlet	9		0.64	0.49	0.15	8000-12000
Riiser Larsen Ice Shelf	10		0.99	0.97	**0.81****	8000-12000
Atka Bay/Atka	11		1	1	0.98	4000-8000
Sanae	12		0.89	0.84	0.80	2000-4000
Astrid Coast Ice Tongue	13		0.88	0.80	0.56	0-2000
Lazarev Ice Shelf/Lazarev	14		0.82	0.73	0.67	0-2000
Ragnhild Coast	15	Indian Ocean	1	1	0.95	4000-8000
Gunnerus (Riiser Larsen Peninsula)	16		1	1	0.95	4000-8000
Umbeashi Rock (Umebosi)	17		0.98	0.96	0.90	0-2000
Amundsen Bay	18		1	1	0.93	0-2000

Kloa Peninsula/Point	19		1	0.99	0.72	2000-4000
Fold Island	20		0.97	0.92	0.45	0-2000
Taylor Glacier	21		0.93	0.86	0.48	0-2000
Auster	22		0.91	0.82	0.34	4000-8000
Cape Darnley	23		0.85	**0.74**	0.29	2000-4000
Amanda Bay	24		0.88	**0.80**	0.41	4000-8000
Haswell Island	25	Western Pacific Ocean	0.88	0.80	0.59	2000-4000
Shackleton Ice Shelf	26		0.83	0.75	0.43	4000-8000
Bowman Island	27		0.83	0.76	0.44	0-2000
Petersen Bank	28		0.84	0.77	0.44	2000-4000
Dibble Glacier	29		0.76	0.70	0.58	12000-16000
Pointe Geologie	30		**0.92***	**0.83**	0.58	2000-4000
Mertz Glacier West	31		**0.72****	0.60	0.31	2000-4000
Davis Bay	32		**0.72****	0.59	0.29	0-2000
Cape Roget	33	Ross Sea	**0.69****	0.58	0.21	8000-12000
Coulman Island	34		0.36	0.24	0.04	16000+
Cape Washington	35		0.39	0.26	0.08	8000-12000
Franklin Island	36		0.37	0.21	0.02	4000-8000
Beaufort Island	37		0.37	0.24	0.07	0-2000
Cape Crozier	38		0.36	0.21	0.02	0-2000
Cape Colbeck	39		0.38	0.26	0.08	16000+
Rupert Coast	40		0.64	0.53	0.28	0-2000
Mount Sipple (Thurston Glacier)	41	Bellingshausen-Amundsen Seas	0.78	0.69	0.43	2000-4000
Bear Peninsula	42		0.76	0.66	0.43	8000-12000
Brownson Islands	43		0.76	0.69	0.51	4000-8000
Noville Peninsula	44		0.77	0.70	0.50	2000-4000
Smyley Island	45		0.85	0.80	0.64	2000-4000

High Emissions Scenario – Representative Concentration Pathway (RCP) 8.5

~~Under this scenario, the~~The response of the emperor penguin population to climate change is also projected under RCP 8.5, ~~the 'business-as-usual'~~ a scenario that represents a future in which greenhouse gas emissions continue unabated (Jenouvrier et al. 2019, p. 3). RCP 8.5 is not necessarily a 'business-as-usual' scenario, but neither is it a worst-case scenario. It represents a plausibly higher level of greenhouse gas concentrations in the atmosphere, broadly consistent with high warming scenarios (USGS 2020, p. 10). As in the low emissions scenario, the research presented here also ~~This scenario~~ uses~~s~~ the output from the Community Earth System Model Large Ensemble project (CESM-LENS)~~), which is the model used in the lower emissions scenarios~~. ~~Simulations used large ensemble member runs~~Ensemble members were run from 1920–2100 with historical forcing~~s~~ over the 20th century and the RCP 8.5 emissions scenario for the 21st century. Using a large ensemble of simulations allows an assessment of the internal variability of the model (Jenouvrier et al. 2019, p.4).

Commented [HZ22]: This was already stated earlier, and I am wondering if it is actually useful here unless you go into more detail about internal variability, otherwise it's somewhat distracting

Resiliency
Similar to Scenarios 1 and 2, the colonies in the eastern Weddell Sea and Indian Ocean on Queen Maud, Enderby, and Kemp Lands will be substantially affected. These colonies will likely experience complete loss of sea ice during the laying season, which is a critical time during the breeding cycle. Additionally, under this high emissions scenario, all the colonies in the Western Pacific Ocean and Bellingshausen and Amundsen Seas are projected to decline by more than 90%. Very few colonies are projected to remain in the Ross Sea and western Weddell Sea. However, even the populations at these colonies are declining at the end of the century.

Annual mean Antarctic sea ice declines by 48%, ~~-~~and 85% (46 of 54) of all colonies are likely to decline by more than 90% by 2100. The colonies that are projected to decline by more than 90% all experience larger than 50% decline in sea ice~~,~~ relative to the historical mean during the laying season (Jenouvrier et al. 2019, p. 9). By 2060, most colonies experience declines larger than 50%~~,~~ relative to historical levels during the nonbreeding and laying seasons. By the end of the century, some colonies are likely to suffer a complete loss of sea ice during the nonbreeding, incubation, and laying seasons.

The total population of emperor penguins is projected to decline by 86%, if dispersal behavior is not considered. Simultaneously, the annual growth rate will decrease by approximately 4% annually. When considering a dispersal scenario that leads to the most optimistic population outcome (short-distance dispersal, low emigration rate, and informed search), the median of the population is projected to decline by 81%. Larger declines are projected with other dispersal scenarios, including up to a 99% decline with long-distance dispersal, high emigration rate, and regardless of dispersal behavior (random or informed search). By including all uncertainties, the 90% confidence envelope of the population projections by 2100 ranges from a decline of 67–99%, relative to the 2010 population size (Jenouvrier et al. 2019, pp. 6–10; Figure 5.3.1).

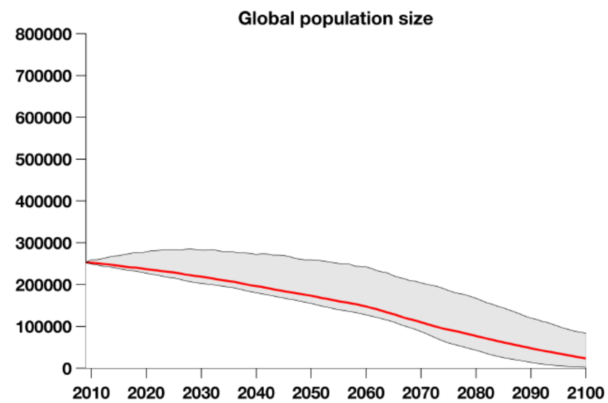


Figure 5.3.1. Projected total number of breeding pairs from 2010 to 2100, accounting for uncertainties of demographic models. The thick red line is the median; the gray area is the 90% confidence envelope (Jenouvrier et al. 2019b, p. 171).

Redundancy

Under RCP 8.5, the redundancy of the emperor penguin will decrease substantially as 85% of the colonies around the continent are likely going to decline by more than 90%, if not disappear, by the end of the century due to poor sea ice conditions (see Figure 5.3.2). Emperor penguins at certain colonies may migrate to higher quality habitat as sea ice conditions worsen over time, although by the end of the century colonies with suitable habitat have likely reached carrying capacity. Under RCP 8.5, the probability was calculated for the number of breeding pairs that decline by more than a specified threshold by 2100 (Jenouvrier et al. 2014, 2017). The likely outcome is defined the same way as it was in the low emissions scenario.

The probability of breeding pair decline was calculated for 54 colonies. All colonies except Gould Bay (in the Weddell Sea) and Cape Crozier (in the Ross Sea) (52 of 54 colonies or 96%) are likely to decline by more than 30%. All colonies except these two colonies, plus the Franklin Island and Beaufort Island colonies—that are both in the Ross Sea—(50 of 54 colonies or 93%) are likely to decline by more than 50%. Most ~~All~~ colonies (46 of 54 colonies or 85%) except Smith Peninsula, Gould Bay, and Luitpold Coast (all in the Weddell Sea); and Cape Washington, Franklin Island, Beaufort Island, Cape Crozier, and Cape Colbeck (all in the Ross Sea), ~~(46 of 54 colonies or 85%)~~ are likely to decline by more than 90%. (Figure 5.3.2; Tables 9 and 10).

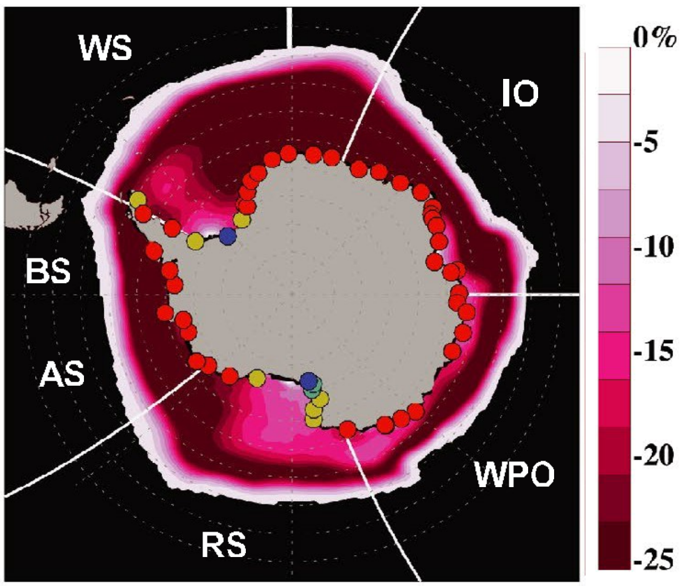


Figure 5.3.2. Annual mean change of SIC between 20th and 21st centuries and conservation status of emperor penguin under RCP 8.5. The conservation status: red - quasi-extinct; yellow - endangered; green = vulnerable; and blue - stable. Note that this figure is based on simulations that did not include dispersion (Jenouvrier et al. 2019, p. 9).

Representation

The emperor penguin would lose genetic diversity with the substantial decline of most of the breeding colonies outside of the western Weddell Sea and Ross Sea. The colonies that make up the known metapopulations in East Antarctica, along with the other colonies in the eastern Weddell Sea and Bellingshausen and Amundsen Seas, are likely to decline by more than 90%. The colonies within the Ross Sea are genetically distinct from colonies in East Antarctica and the Weddell Sea and would be the last stronghold for the species at the end of the century (Younger et al. 2015, p. 2219; Younger et al. 2017, p. 3893). Penguins may migrate to the Ross Sea as habitat quality declines around the continent. However, by the end of the century, the colonies that remain have likely reached carrying capacity and some colonies provide little potential for population expansion (Jenouvrier et al. 2014, p. 716). Even the colonies in the Ross Sea are declining at the end of the century. Therefore, the genetic diversity of emperor penguins will substantially decrease because the vast majority of all colonies around the continent of Antarctica are likely going to decline by more than 90%, if not disappear entirely.

Table 9. Conservation Status/Probability of Decline of the Emperor Penguin Colonies under the high emissions scenario. Colony No. is relative to Figure 5.2.2. Bolded probabilities represent the colonies that do not reach the conservation status.

Commented [HZ23]: Just a thought: This may be ridiculous, but have you tried bolding all the colonies that *do* reach conservation status instead? It might get the point across even more obviously if nearly everything is bolded, otherwise you are emphasizing those colonies that are likely to stick around, but there's a whole lot more that won't

Conservation Status RCP 8.5

Colony Name	Colony No.	Sector	Vulnerable >30%	Endangered >50%	Quasi-extinct >90%	Population Size (2019)
Snow Hill	1	Weddell Sea	1	0.9976	**0.377**	2000-4000
Jason Peninsula (Larsen Ice Shelf)	2		1	1	0.9992	0-2000
Dolleman Island	3		1	1	0.9906	2000-4000
Smith Peninsula	4		0.985	0.89	**0.0218**	2000-4000
Gould Bay	5		**0.5864**	**0.2064**	**0**	4000-8000
Luitpold Coast	6		0.9956	0.9532	**0.02**	4000-8000
Halley Bay	7		1	1	0.8638	8000-12000
Dawson-Lambert Ice Tongue	8		1	0.9998	0.8102	12000-16000
Stancomb-Wills Glacier	9		1	1	1	4000-8000
Drescher Inlet	10		1	1	1	8000-12000
Riiser Larsen Ice Shelf	11		1	1	1	8000-12000
Atka Bay/Atka	12		1	1	1	4000-8000
Sanae	13		1	1	1	2000-4000
Astrid Coast Ice Tongue	14		1	1	1	0-2000
Lazarev Ice Shelf/Lazarev	15		1	1	1	0-2000
Ragnhild Coast	16	Indian Ocean	1	1	1	4000-8000
Gunnerus (Riiser Larsen Peninsula)	17		1	1	1	4000-8000
Umbeashi Rock (Umebosi)	18		1	1	1	0-2000
Amundsen Bay	19		1	1	1	0-2000
Kloa Peninsula/Point	20		1	1	1	2000-4000
Fold Island	21		1	1	1	0-2000
Taylor Glacier	22		1	1	1	0-2000
Auster	23		1	1	1	4000-8000
Cape Darnley	24		1	1	1	2000-4000
Amanda Bay	25		1	1	1	4000-8000

Barrier Bay	26		1	1	1	0-2000
West Ice Shelf	27		1	1	1	0-2000
Burton Ice Shelf	28		1	1	1	0-2000
Haswell Island	29	Western Pacific Ocean	1	1	1	2000-4000
Shackleton Ice Shelf	30		1	1	1	4000-8000
Bowman Island	31		1	1	1	0-2000
Petersen Bank	32		1	1	1	2000-4000
Sabrina Coast	33					0-2000
Dibble Glacier	34		1	1	1	12000-16000
Pointe Géologie	35		1	1	1	2000-4000
Mertz Glacier West	36		1	1	0.9144	2000-4000
Mertz Glacier East (Break Off)	37		1	1	0.855	4000-8000
Davis Bay	38		1	0.999	0.7458	0-2000
Cape Roget	39	Ross Sea	0.968	0.8156	**0.0058**	8000-12000
Coulman Island	40		0.971	0.818	**0.0072**	16000+
Cape Washington	41		0.9934	0.9392	**0.0512**	8000-12000
Franklin Island	42		0.7954	**0.4142**	**0**	4000-8000
Beaufort Island	43		0.7138	**0.3042**	**0**	0-2000
Cape Crozier	44		**0.5006**	**0.146**	**0**	0-2000
Cape Colbeck	45		0.979	0.869	**0.0286**	16000+
Rupert Coast	46		1	1	0.9932	0-2000
Ledda Bay	47		1	1	1	0-2000
Mount Sipple (Thurston Glacier)	48	Bellingshausen-Amundsen Seas	1	1	1	2000-4000
Bear Peninsula	49		1	1	1	8000-12000
Brownson Islands	50		1	1	1	4000-8000
Noville Peninsula	51		1	1	1	2000-4000
Bryan Coast	52		1	1	1	0-2000
Smyley Island	53		1	1	1	2000-4000
Rothschild Island	54		1	1	1	0-2000

Overall future conditions summary

The three future scenarios based on existing work projecting sea ice conditions and the response of emperor penguins shows a range of population effects at the colony and population levels, similarities between scenario outputs, and the increasing risk to emperor penguin viability under the high emissions scenario. Two of the three scenarios show similar patterns – the low emissions scenario (~~of~~ Paris 1.5 and Paris 2) and the moderate emissions scenario (~~of~~ SRES A1B/~~ (~~RCP 6.0). Both of these scenarios project that the breeding colonies in the eastern Weddell Sea and Indian Ocean i~~o~~n Dronning Maud, Enderby, and Kemp Lands are likely to be the least resilient and experience the largest population decline and sea ice decrease and variability. Projected changes in other regions such as the Bellingshausen-Amundsen Seas are more complex and vary according to seasons, region, and emissions scenario. In all scenarios, the Ross Sea and western Weddell Sea colonies are likely to be the most resilient. Under the high emissions scenario, all colonies in four of f~~the f~~ive sectors and the vast majority of breeding colonies ~~rangewide~~ across all sectors decline significantly. The colonies in the Ross Sea will likely serve as the last refuge for the species. Under lower emissions scenarios, multiple resilient colonies exist compared to the very few that remain under the high emission scenario. Redundancy and representation are highest under the low and moderate emissions scenarios because multiple resilient colonies remain in more of the five sectors compared to the high emissions scenario, where colonies only remain in the Ross Sea and western Weddell Sea.

Commented [HZ24]: It may help to add some discussion about how unlikely it is that we will only reach the Paris goal of 1.5-2˚C of warming given that we *still* aren't doing much to combat climate change. This means that Emperor penguins might experience something more along the lines of the moderate to high emissions scenarios, which I think is important to point out. I have not kept up with the literature on this recently, but I am sure there are papers out there about this that may help support a commentary like that, specifically ones about the warming that we've probably already 'locked in' or committed to.

Table 10. Comparison between the three scenarios of the projected population of the emperor penguin at the end of the 21st century.

Scenario Output Comparison Table at the end of 21st Century	**Scenarios**			
	(RCP 2.6–4.5)		**(RCP 6.0)**	**RCP 8.5**
	Paris 1.5	**Paris 2**	**SRES A1B**	
Global Temperature Increase (°C)	1.5 °C	2 °C	3 °C	5 °C
Annual Mean Sea Ice Decline (%)	5%	13%	X	48%
Median Population Decline (%)	31%	44%	78%	86%
Median population growth rate (%)	-0.07%	-0.34%	-3.2%	-4%
Percentage of total colonies likely* to decline by >30%	61%	67%	76%**	96%
Percentage of total colonies likely* to decline by >50%	54%	63%	62%**	93%
Percentage of total colonies likely* to decline by >90%	19%	31%	20%**	85%

* A likely outcome is defined by the IPCC as a term to indicate the assessed likelihood of an outcome or a result (likely 66–100%).
** Under SRES A1B, a local, pan-Antarctic, and all-models simulation were analyzed, giving the range of outcomes. The pan-Antarctic population decline is higher because of higher loss of sea ice.

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